PREDICTING CHANGE IN RESIDUAL EXTRACTABLE P FOR SITE SPECIFIC MANAGEMENT IN PADDY SOILS OF INDONESIA

A DISSERTATION SUBMITTED TO THE GRADUATE DIVISION OF THE UNIVERSITY OF HAWAI'I IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF

DOCTOR OF PHILOSOPHY

IN

AGRONOMY AND SOIL SCIENCE

DECEMBER 1996

By

Martinus H. Pandutama

Dissertation Committee:

Russell S. Yost, Chairperson
Muhammad A. Khan
Carl I. Evensen
Rollin C. Jones
James A. Silva

We certify that we have read this dissertation and that, in our opinion, it is satisfactory in scope and quality as a dissertation for the degree of Doctor of Philosophy in Agronomy and Soil Science.

DISSERTATION COMMITTEE

Russell Yost
Chairperson

M. Akram Khan

Carl Evans

Lollie Y. Jones

James A. Silva

I dedicate this work to:

my Wife Nanik,

my Daughter Jasmine (Jessie),

to my Parents, and all my Siblings.

ACKNOWLEDGEMENTS

I wish to express my sincere gratitude to those who make the study possible: 1) to the Program on Environment (ENV) formerly the Environmental and Policy Institute (EAPI) at the East-West Center, and to the Soil Management - Collaborative Research Support Program (SM-CRSP) for providing financial support throughout my study at the University of Hawai'I at Manoa and for my field research; 2) to the Centre for Soil and Agroclimate Research (CSAR), Bogor-Indonesia, for providing greenhouse facilities and housing during my field research in Bogor.

I am greatly indebted to Dr. Russell S. Yost, my principal advisor, for his invaluable guidance, encouragement, and spending countless hours reviewing and improving this dissertation. I would also like to express my appreciation to my committee members, Drs. Muhammad A. Khan, Rollin C. Jones, James A. Silva, and Carl I. Evensen, for their advice, suggestions and contributions during the course of my research and toward improvement of this dissertation. I also am in greatly indebted to Dr. Goro Uehara for providing the idea of using clay physical activity in the model, and for his support and suggestions during my research.

My special gratitude is also addressed to Dr. Gordon Y. Tsuji and all of the IBSNAT staff for their kindness. They provided a hiding place to work and other facilities toward finishing my dissertation. Many thanks also to Dr. James H. Fownes for sharing his ideas regarding net desorption.

I would also like to extend my appreciation to all my fellow graduate students at the Department of Agronomy and Soil Science, especially to Michael Constantinides, James Jackman, Phoebe Kilham, Chanchai Sangchyoswat, Carrie Babcock, Jonathan Deenik, Robert Abaidoo, and Xinmin Wang, for their help in so many ways and providing me with much needed support throughout my studies.

Finally, I am especially indebted to my wife Nanik, and my daughter Jasmine (Jessie). Without their love, patience, encouragement, and understanding this whole work would not have been possible.

ABSTRACT

Paddy-soils in Java, Indonesia, have been intensively fertilized with nitrogen (N), phosphate (P), and potassium (K) for at least three decades through centralized government subsidy programs, such as BIMAS, INMAS, INSUS, and SUPRA-INSUS. One side effect of these programs has been an accumulation of soil phosphorus (P) to excessive levels. The N, P, and K nutrients were added to all fields in rice production without modification for soil P status or for soil properties.

The goals of this study were to: 1. ensure sustainable rice production; 2. improve nutrient efficiency; and 3. improve phosphate management in paddy soils to reduce both fertilization cost and environmental hazards. The objective of this study was to develop a mathematical model to predict how long P fertilization could be suspended and how to tailor P fertilization to soil criteria.

A mathematical model was developed to predict extractable P as a function of frequently measured soil properties, namely initial extractable P, pH, clay content, organic carbon content, and clay physical activity. The model for HCl-extractable P status in paddy rice soil was:

$$EP_t = \{0.67\ EP_i - 11.63\} + (22.26\ OC) + (0.006\ CLAY\ \ P) + \{59.13\ OC\ EXP(-(-0.14 + 0.32\ CAT)\ \ Time)\}$$

The resulting model was combined with a geographical information system (GIS) software, ARC/INFO, to map P status and to predict the change in extractable

P of paddy soils of Java with successive cropping. The model was also used to estimate site specific P recommendations which then mapped and analyzed by GIS. Two scenarios of the P fertilization strategies were considered:

1. A) Fifty kg TSP ha^{-1} would be applied to soils with medium and high extractable P, applied in every 4 crops; B) Fifty kg TSP ha^{-1} for soils low in extractable P, applied in every crop. And,
2. A) Fifty kg TSP ha^{-1} would be applied to soils high in extractable P, applied once every 8 crops; B) Fifty kg TSP ha^{-1} for soils medium in extractable P, applied once every 4 crops; and C) Fifty kg TSP ha^{-1} for soils low in extractable P, applied to each crop.

Approximately 85 000 to 94 000 tonnes of TSP fertilizer per crop would be saved compared to the Centre for Soil and Agroclimate Research (CSAR)/ government recommendations if the first and second scenarios were followed, respectively. The CSAR/government recommendations are: 1. Fifty kg TSP ha^{-1} applied to soils high in extractable P, once every four crops; 2. Seventy-five kg TSP ha^{-1} applied to soils medium in extractable P, two times every four crops; and 3. One hundred twenty-five kg TSP ha^{-1} applied to soils low in extractable P, every crop.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

CHAPTER 1. INTRODUCTION

Phosphatic fertilizers applied to soils are subject to chemical transformations into less available forms. Reactions occur among phosphate, soil constituents, and nonphosphatic fertilizer compounds that remove phosphorus (P) from the solution phase and render the phosphates less soluble or less available to plants. This phenomenon is called P fixation or P retention (Way, 1850). Wild (1950) cited several researchers from the mid-nineteenth century who concluded that calcium carbonate ($CaCO_3$) and hydrous oxides of iron (Fe) and aluminum (Al) played key roles in P retention. They suggested that the P was either precipitated as Ca-, Fe-, or Al-phosphates or that the P was chemically bonded to these cations at the surfaces of the soil minerals.

Highly weathered tropical soils are often deficient in P as a natural consequence of the presence of aluminum and iron oxides (Fox and Searle, 1978; Sanchez and Uehara, 1980; Wade and Widjaja-adhi, 1988). This alone, however, should not be the reason for continued use of P fertilizers. Compiled evidence indicates that a large portion of the P remaining after the first crop year is not "fixed" and is available to subsequent crops. Residues resulting from continued fertilization of soils have caused accumulation of available P to the extent that this frequently ignored nutrient reservoir has acquired both agronomic and economic significance for succeeding crops. Such availability has been referred to as residual available P

(Sadler and Stewart, 1974; Fixen and Ludwick, 1982). (Note: for more general purposes the term residual extractable P is used in this study). Most soils, even those initially deficient in P, accumulate P when applications exceed removals. This was apparently the cause of excessive accumulation of extractable P in paddy soils (Sri Adiningsih *et al.*, 1988; Yost *et al.*, 1992).

It is difficult to predict how much P must be added to provide the increase in the extractable P needed due to the complexity of P-soil interactions. Only a small proportion of the added P remains extractable, while the rest is retained by the soil constituents and is less available to plants. Kamprath (1967), found that an application of 687 kg of P/ha was adequate to support corn for 7 to 9 subsequent years, which indicated that the residual value was significant.

The amount of P removed from the field is dependent on the kind of crop grown. Annual removal by irrigated alfalfa is high and may reach 60 kg of P/ha (Leamer, 1963). In countries where P fertilizers are widely used, the amount of P removed by the crop is, on the average, only a small proportion of the amount added. For example, for the whole of Australia, the amount of P removed from farms is now less than 20% of that applied in fertilizer (Gifford *et al.*, 1975). Since the amount removed includes produce from the unfertilized areas, the amount removed from the fertilized areas may be less than this. Larsen (1974) estimated that for Denmark the amount removed is only about 10% of that applied. Matar *et al.* (1988) found that an

average removal of 6% of the added P was observed in the low rainfall barley zones, and about 10% in the wetter wheat belt.

The amount of P removed in grain and straw is generally low -- approximately 15 to 20% of the plant dry weight. Thus, a large amount of residual P remains in the soil after harvest. The expected decrease in the extractable P (in this case the residual available P) is thought to result from two components. The first component is the continuation of slow reactions lasting for weeks or months. The second results from the amount of P removed by the crop (Matar, 1989; Li *et al.*, 1995).

Mechanistic models have been used to predict the residual P and residual effect of P in soils (Russell, 1977; Barrow and Carter, 1978). Descriptive models for residual P based on chemically extractable P in soils have also been developed by Cox *et al.* (1981), and improved by Lins *et al.* (1985). The last two models, did not directly include P uptake by the crop from the soil, however, it was included as an aggregated effect in the buffer coefficient. Matar (1989), in further improving a descriptive model for prediction of residual P in soil, added a separate item representing P uptake by the crop. However, he did not further analyze the relationship of residual availability of P with the soil properties responsible for the availability of soil-P. Li *et al*, (1995) further improved the model for predicting extractable P after the crop and included both crop uptake and soil properties in their model for predicting extractable P after crop harvest.

Paddy soils in Java, Indonesia have been intensively fertilized with P (in the form of TSP) for at least three decades through government subsidized intensification packets to the farmers. This centralized decision making has had some unfortunate side effects, however. One effect has been the growing imbalance of nutrients in paddy fields of Java. Imbalances have occurred due to differences in reaction between soils and nutrients. Repeated applications of nitrogen and potassium seldom accumulate because their retention in the soil is far less than that of phosphorus. Soils with low P sorption capacity will accumulate more extractable P than those with high P sorption, in some cases to excessive levels. Sri Adiningsih *et al.* (1988), found that adding P fertilizer at 25%, 50%, 75% and 100% of the recommended rate to up to four consecutive rice crops gave yields that were not significantly greater for four consecutive crops. This lack of response to added P occurred for 13 of 15 locations on Java island. In addition, Karama (1993) stated symptoms of zinc (Zn) deficiency on rice have been found presumably as a result of too much P accumulation in paddy soils of Java.

Based on this research, reducing the frequency and amount of P-fertilizer applied should be considered seriously. Increasing fertilizer-utilization efficiency is becoming a crucial factor in improving productivity of low fertility soils, and maintaining the nutrient balance in fertile soils. Knowledge of residual P and the residual extractable P, and the appropriate means of quantifying them, is essential for efficient fertilizer utilization.

Phosphorus recommendations can not be generalized to all soils. They must be specific for specific soils. A model that uses soil testing and crop information to generate a site specific recommendation will improve on the strategy of one recommendation for all soils.

Objectives

Because of the lack of a detailed understanding between the rates of sorption and desorption of P with related soil properties in previous models, the objectives of this study were: 1. To develop technology to improve phosphorus fertilizer recommendations for rice by developing a mathematical model of residual extractable phosphorus over time, reflecting both soil and crop influences; 2. To generate updated maps of the phosphorus status of Java soils; 3. To improve the soil phosphate management for paddy soils of Java.

The goal of this study is to improve phosphate management especially in paddy soils to ensure sustainable rice production as well as reduce both fertilization cost and environmental hazard.

CHAPTER 2. LITERATURE REVIEW

2. 1. Phosphorus Adsorption by Soil Constituents

When considering the continuing reaction between soil and phosphorus (P), many researchers have thought in terms of a model in which the P is present in at least three different categories. One of these is phosphate in the soil solution and another is phosphate adsorbed on the soil particles and in quasi-equilibrium with the solution (Wiklander, 1950; Williams, 1952; Larsen, 1967, 1974; Barrow & Shaw, 1975). The third category comprises P which is variously described as fixed on the surface layers of the soil particles (Wiklander, 1950; Williams, 1952), retention (Sample, *et al.*, 1980), non-labile (Larsen, 1967, 1974), or in form which is not in direct equilibrium with the solution (Barrow & Shaw, 1975). Barrow (1980), also stated that there is probably an uncertainty about the nature of this third category, but in all cases the essence is the implication that the P is more firmly held and is less readily available to plants. When any previous equilibrium between these categories is disturbed by adding P-fertilizer, it is envisaged that reaction between soil and P in solution takes place in two steps,-- a rapid step in which some of the phosphate is adsorbed, and a slower step in which some of the phosphate is converted into a more firmly held form.

Phosphorus (P) adsorption by soils is a widely researched subject. This is primarily because of the widespread P deficiency reported for agricultural soils, and

the fact that P adsorption by soil is a process mainly responsible for rendering soluble phosphate in soil solution unavailable to plants. The adsorption process, which refers to surface P accumulation on soil components, may, in some cases, be accompanied by penetration of the adsorbed P by diffusion into the adsorbent body, leading to further absorption of the adsorbed species. The general term ***sorption*** is sometimes used to denote both of these processes taking place simultaneously (Sanyal and De Datta, 1991).

2. 2. Factors Affecting Phosphate Adsorption

Many soil properties influence P adsorption by soils. These include the nature and amount of soil components, such as clay, organic matter, and hydrous oxides of iron and aluminum; background electrolyte -its concentration, and valency of the constituent cation; and pH of the adsorption system.

2. 2. 1. Hydrous Oxides of Iron (Fe) and Aluminum (Al)

Iron (Fe) and aluminum (Al) oxides and hydrous oxides can occur as discrete compounds in soils or as a coating on other soil particles. They can also exist as amorphous Al hydroxy compounds between the layers of expandable Al silicate (Sample et al., 1980). Wild (1950), stated that as early as 1866 Warington found that hydrous oxides of Fe and Al retained large amounts of P from solution and that the amount of P retained in a soil was related to hydrochloric acid-soluble Fe and Al, particularly in acid soils. Recent research, however, found that acid ammonium oxalate extractable (amorphous) Fe and Al proved to be an important criterion for P

adsorption in several soils, (Juo, 1981; Borggaard, 1983; Araki *et al.*, 1986; Loganathan *et al.*, 1987; Adams *et al.*, 1987; Wada *et al.*, 1989; Buchter *et al.*, 1989).

Oxalate extraction is known to dissolve amorphous and poorly crystalline oxides of iron and aluminum while having little or no effect on crystalline iron and aluminum minerals. Crystalline Fe oxides are relatively inactive in P sorption (Ryden and Pratt, 1980). Sanyal and De Datta (1991) stated that the difference in P adsorption capacity (PAC) between fresh soil, and soil after extraction with oxalate showed that a high proportion of P adsorption by soils from 11 horizons of an acidic soil was attributable to poorly ordered minerals.

The role of oxides and hydroxides of iron and aluminum in retaining inorganic P was also emphasized by Ryden and Pratt, 1980, who found that short-range (amorphous) iron oxide gels, in general, sorb 10-100 times more P than do crystalline iron and aluminum hydrous oxides (e.g., hematite and gibbsite), and approaching 1000 times more than do crystalline aluminosilicates and calcium carbonate.

Phosphorus adsorption reactions that occur with Fe and Al at clay and oxide surfaces have been proposed to be exchange reactions. Phosphate enters into coordination with metal ions at oxide surfaces by means of ligand exchange. Initially, other anions or water molecules are at these surfaces, forming a complex (Hingston *et al.*, 1968, 1972; Parfitt *et al.*, 1975).

The initial fast reaction of P sorption is commonly stated as a ligand exchange reaction that form a monodentate bond of phosphate to Fe or Al (Olsen and Khasawneh, 1980). Researchers generally agree that the initial reaction is a ligand exchange reaction, while the slow reaction has been difficult to characterize and several mechanisms have been suggested (Sanyal and De Datta, 1991).

Parfitt *et al.* (1975) indicated that, based on infrared studies, P was specifically adsorbed by Fe oxide surfaces by replacing two adjacent surface hydroxyl ions. Two oxygen atoms of the phosphate ion are linked to two Fe ions giving a binuclear surface complex, Fe-O-(OH-P=O_2)-O-Fe. Rajan (1975) also suggested, by calculating the number of hydroxyls released, that the adsorption of HPO_4^{2-} by hydrous Al oxides is due to binuclear coordination of phosphate ions with two Al atoms. Therefore, P may become strongly bound to hydrous oxides of Al and Fe and be relatively unavailable to plants (Sample *et al.*, 1980).

2. 2. 2. Alumino-silicate Minerals

A significant correlation of P sorption with clay content has been reported by several researchers, and this may be a mere reflection of the effect of specific surface area on P adsorption (Sanyal and De Datta, 1991). Wild (1950), concluded that, when compared at nearly equal surface areas, however, montmorillonitic and kaolinitic clays retained similar amounts of P. Sanyal and De Datta (1992) added that, clays, particularly (1:1) lattice clays, may contribute to P sorption in tropical soils, especially at low pH, when the activity of Fe and Al is also expected to be

higher. Adsorption on to minerals illite, smectite and kaolinite has been measured to occur at low concentrations of P in solution, less than 10 mg P L^{-1}, above this range the surface dissolution of the clay minerals begins to occur and cause precipitation of aluminophosphates (Norrish and Rosser, 1983).

There have been numerous studies of sorption by clay minerals in which one of several adsorption isotherms has been used to mathematically describe the sorption data. Because of similarities in the sorption isotherms for alumino-silicates and the hydrous oxides, several researchers concluded that the sorption mechanisms are the same for the mineral groups (Sample *et al.*, 1980).

Hydrous oxides of Fe and Al have been found to occur as fine coatings on surfaces of clay minerals in soil. These coatings, characterized by large surface areas, hold an appreciable quantity of P, thereby implying a secondary role of crystalline alumino-silicates (clays) in P sorption (Sanyal and De Datta, 1991).

2. 2. 3. Soil Carbonates

The reactions of P with pure carbonates have been studied in some detail considering the domination of the chemistry of soil carbonates in calcareous soils. Adsorption reactions dominated when dilute P solutions were added to $CaCO_3$, but precipitation reactions dominated with more concentrated P solutions. The mechanism of P adsorption by $CaCO_3$, however, is still not well understood (Samples *et al.*, 1980). Kuo and Lotse (1972) suggested that P may replace adsorbed water molecules, bicarbonate ions, and hydroxyl ions when it is adsorbed by calcite.

And the adsorbing strength depending upon the solubility of the compound formed with the surface Ca ions. Griffin and Jurinak (1973, 1974) also found that two reactions were occurring. The first reaction at low P concentrations consisted of the adsorption of P by the calcite surface. The second reaction was described as a nucleation process of calcium phosphate crystals where there is a surface rearrangement of amorphous phosphate into phosphate heteronuclei which supersedes crystal growth. Sample *et al.* (1980) indicated that, by solubility studies, hydroxyapatite was formed at low P concentration. At higher P concentration the solutions were saturated with octocalcium phosphate.

There is some discrepancy about the mineral formed upon precipitation of calcium with phosphate as some research has reported that dicalcium phosphate develops or physical adsorption takes place. With time and whatever the initial form of phosphate is, upon removal from solution, it should slowly convert to apatite (Berkheiser *et al.*, 1980; Norrish and Rosser, 1983).

Afif *et al.* (1993) found sorption in calcareous soils was correlated with silicate clay content and Fe oxides when the amount of P applied was relatively low. At high levels of applied P the sorption was correlated with calcium carbonate content.

2. 2. 4. Soil pH

Several P sorption parameters have been noted having a strongly negative correlation with soil pH. This agrees with several observations and agrees with

what has been stated regarding the activity of Fe and Al at low pH (Sanyal and De Datta, 1991).

Freshly precipitated Fe and Al oxides at pH 6.5 were responsible for the increased P sorption. Phosphorus adsorption on goethite was also found to be less dependent on pH when $CaCl_2$ rather than NaCl was used as the indifferent electrolyte (Parfitt, 1978). Naidu *et al.* (1990) reported an increase in P sorption by strongly acidic soils on liming after an initial fall, and beyond pH 5.5-6.0. This rise was attributed to the formation of insoluble Ca-P compounds. Smillie *et al.* (1987) also suggested that a chemical association between sorbed P and Ca in soils having adequate exchangeable Ca is an important P retention mechanism.

Sanyal and De Datta (1992) found that, with an increase in pH, the charge and the electrostatic potential of positive sites on variable-charge materials in soil decrease, causing a fall in P retention. However, at higher pH (>5.0), the concentration of deprotonated $H_2PO_4^-$ (i.e., of $HPO_4^=$ ion) increases, which generally the dominant adsorbable species (e.g., on goethite). This encourages the P adsorption by goethite at higher pH up to a pH of 7.0. Therefore, P adsorption by goethite and amorphous hydroxy-Al surfaces decrease relatively slowly up to pH 7.0, and rapidly decreases beyond pH 7.0.

Electrolyte concentration and valence of cation affect the electrostatic potential on the surface. An increase in concentration of polyvalent cations of the electrolyte, renders the potential on the surface less negative (Bowden *et al.*, 1980;

Barrow, 1987), and the effect of higher pH in bringing down P adsorption is less marked (Sanyal and De Datta, 1991). This also causes desorption of the previously adsorbed P to decrease (Barrow and Shaw, 1979).

2. 2. 5. Soil Organic Matter

The correlation between organic matter and phosphate sorption could be both positive and negative (Sanyal and De Datta, 1991). The positive correlation is related to humus in association with cations such as Fe^{3+}, Al^{3+}, and Ca^{2+} which is able to retain significant amount of P (Wild, 1950). The role of organic matter in augmenting P sorption in soil has often been attributed to the association with and possible stabilization of the soil organic matter by the free sesquioxides (Sanyal and De Datta, 1991). Bennoah and Acquaye (1989) also indicated that, Fe and Al intimately associated with organic matter can sorb much more P than can the same amount of free Fe_2O_3 and Al_2O_3. Harter (1969), however, disagreed with the idea that organic matter and P were adsorbed in soil by the same mechanism, and suggested that P may even be directly bonded to organic matter by replacing the organic hydroxyl groups. Appelt *et al.* (1975) believed that the P was adsorbed by ligand exchange of phosphate for hydroxyl groups of hydroxyl-Al-humic acid complex. This was due to the reaction of humic acid with Al from soil minerals to form these complexes, which could rise to new surfaces for P adsorption. The effect of an increase in organic content of the soil therefore would be to increase P adsorption rather than to decrease it by competing with P for adsorptive sites.

Later research, however, found that P sorption is reduced by the increase of organic matter in soils (Sanyal and De Datta, 1991). This can be explained by a possible competitive action between P and organic matter for sorption sites on, for instance, hydrous oxides of Fe and Al. Humic acid and fulvic acid competed strongly with P for adsorption sites on goethite and gibbsite at low pH values.

Organic anions can compete with phosphate for the sorption sites on mineral surfaces and thus block phosphate from being sorbed. Low molecular weight organic acids have been shown to decrease phosphate sorption of various minerals and soils when they were applied with the P or even more effectively when they were applied before P applications. These treatments allowed for more complete sorption of the organic anions before the phosphate could compete for the sites (Hue, 1991).

Soil organic matter is very complex, especially in terms of composition and interaction with soil minerals. Thus, its effects on phosphate sorption are difficult to determine.

2. 3. Phosphorus Behavior in Submerged Soils

The behavior of phosphorus (P) in flooded lowland soils remarkably differs from that in upland soils. Besides, rather scant attention has been given to the chemistry of P transformations in flooded soils compared to those in nonflooded soils. Flooding the soil continuously increases the availability of native and added P. Drying a soil subsequent to flooding, however, generally decreases the solubility of both native and applied P (Sanyal and De Datta, 1991).

The rice crop easily adapts to the environment. It can grow in various types of soils under a wide range of climatic and soil moisture conditions. It can be grown with a thin film of moisture on the soil surface, to about 10-50 cm of standing water. It is mostly grown, however, in submerged soils with 10-30 cm standing water during most of its growth period.

Rice can also be grown under continuous flooded soil, or under alternate wetting and drying conditions. These changes in soil moisture conditions in the rice fields affect the changes in soil, which in turn influence the transformation of native and applied P, P-availability, and consequently, rice nutrition and growth. Changes in P availability in alternate flooded and drained soil are also important with regards to the growth of subsequent crops in rotation with rice (Sanyal and De Datta, 1991).

2. 3. 1. Phosphorus Transformations Flooded Condition

Phosphorus availability in soil increases upon submergence due to the following changes (Ponnamperuma, 1985; Sanyal and De Datta, 1991):

a. Reduction of ferric compounds. The reduction of free hydrous Fe oxides during flooding, and the liberation of sorbed and coprecipitated P as a result increased the levels of solution or extractable P in flooded acidic soil.

The chemical equilibria equations of the following types have been used to describe the activity of Fe^{2+} in solutions of flooded soils.

$$Fe(OH)_3 + 3H^+ + e^- = Fe^{2+} + 3H_2O \quad (1)$$

for reduction in the early stages of flooding, and

$$Fe_3(OH)_8 + 8H^+ + 2e^- = 3Fe^{2+} + 8H_2O \quad (2)$$

in soils after prolonged flooding.

Ferrihydrite, the least stable oxide among the ferric hydrous oxides, has been postulated to undergo reductive dissolution (e.g. reaction) first, releasing the sorbed P, in advance of the more stable oxides such as goethite.

A theoretical study of simple chemical systems suggested that reduction of ferric hydrous oxides in the presence of P in solution takes place more easily than in similar solution without P, because of the precipitation of vivianite $Fe_3(PO_4)_2.8H_2O$. However, it was also shown that if P, sorbed onto ferric hydrous oxide, is a significant source of P in soils, then it is the rise in pH (associated with the reduction of Fe^{3+}) rather than the fall in redox potential, E_h (favoring the reductive dissolution of ferric hydrous oxides) that is responsible for the relatively high P concentration in waterlogged soil solutions. An increase in pH would, in fact favor P desorption from clay, aluminum oxides, and excess (not yet reduced) ferric oxide surfaces through a decreased surface positive charge.

b. Higher solubilities of $FePO_4.2H_2O$ (Strengite) and $AlPO_4.2H_2O$ (Variscite) resulted from hydrolysis due to increased soil pH in acid and strongly acid soils.

c. Organic transformations influencing P release. Organic acids released during anaerobic decomposition of organic matter under flooded soil conditions can increase the solubilities of Ca-P as well as Fe-P and Al-P compounds by

complexing Ca^{2+}, Fe^{3+}, and Al^{3+} ions, and thereby disturbing the solubility equilibria of Ca-P, Fe-P, and Al-P.

Mineralization of organic P is generally too slow to be significant in plant nutrition, although mineralization rates increase under flooding. Mineralization of organic P has been considered as a minor source of P in flooded soils, except in flooded organic soils.

d. Release of phosphate ions from the exchange between organic anions and phosphate ions in Fe-P and Al-P compounds.

e. Increased solubility of Ca-P in calcareous soils as a result of pH depression due to CO_2 accumulation by organic matter decomposition.

It has been suggested that the solubility of several Ca-P compounds, such as octacalcium phosphate, *ß*-tricalcium phosphate, hydroxyapatite, and fluorapatite increases following a fall in pH after flooding a calcareous soil.

In acidic soils, such an accumulation of CO_2 under anaerobic conditions would tend to bring down the pH, opposing thereby a pH rise due to reaction (1). This will also cause an increase in HCO_3^- concentration in the solution phase through the solvent action of CO_2 on carbonates, and would cause desorption of several exchangeable cations (e.g. Fe^{2+}, Ca^{2+}, Mg^{2+}, and NH_4^+) to maintain the electroneutrality in solution.

f. Increased P diffusion under submerged conditions. Flooding tends to increase the buffer capacities for soil P. This has been attributed to P adsorption from

soil solution by the reprecipitated poorly crystalline ferrous hydroxides or carbonates from Fe^{2+} ions formed by soil reduction. An increase in pH reduced further P adsorption due to an increase in negative charge of the variable-charge P-adsorbing surfaces in the flooded soil. At the same time, an increase in ionic strength of the solution depresses the activity coefficients of the ionic species in the solution phase. The latter would tend to raise the concentration of phosphate ions and, hence, affect the ionic equilibria between solid-phase P and soil-solution P, opposing P desorption due to pH increase.

g. Phosphorus mobilization resulted from an increased microbial activity in the presence of physiologically active rice roots and from the capacity of rice plants to reoxidize the rhizosphere during the later phase of the growing period.

h. In soils poor in free Fe oxides, under highly reduced conditions, another process, shown in the following conversion increases availability of P in flooded soils:

$$Fe_3(PO_4)_2 + 3H_2S = 3FeS + 2H_3PO_4 \quad (3)$$

Flooding a soil increases the soluble P concentration in the soil and reaches a maximum before falling. The subsequent fall in P concentration after reaching the peak has been attributed to readsorption of P on clays and Al hydroxides, precipitation, or microbial degradation of organic anions at the exchange sites, causing P resorption from soil solution.

During the prolonged flooding, the level of Fe^{2+} iron in solution stabilizes, but the level of acid-extractable Fe^{2+} iron continues to increase. Precipitation of ferrosic (or ferrosoferric) hydroxide, $Fe_3(OH)_8$, was stated to have a large surface area with a high P-sorption capacity. Consequently, this could well contribute to the decline of P concentration in soil solution on continued submergence. However, P thus sorbed may still remain acid-extractable, and contribute to the labile pool of P in soil, and thus remain available to plants.

2. 3. 2. Forms of Phosphorus in Flooded Soils

Extractable P content in flooded soils tends to increase, depending primarily on the distribution of different inorganic P fractions and the intensity of soil reduction (Sanyal and De Datta, 1991).

In general, higher P availability in flooded soils is attributed mainly to Fe-P; while the role of Al-P and Ca-P is usually secondary (Sah and Mikkelsen, 1986a). Willet and Higgins (1978) also found that acetate and oxalate-extractable Fe and P sorptivity of soil largely increased upon flooding.

Sah and Mikkelsen (1986b) found that the anaerobic decomposition of the added cellulose in flooded soils decreased Al-P and increased Fe-P and reductant soluble (RS)-P. They attributed this to an increase, mediated by the anaerobic decomposition of the organic matter, of crystalline Fe transformation into amorphous forms, which, in turn, increased Fe-P and severe occlusion of P, resulting in the increase of RS-P fraction upon subsequent soil drainage.

2. 3. 3. Phosphorus Transformations Under Alternate Wetting and Drying Condition

Drying a soil subsequent to flooding generally decreases the solubility of both native and applied P. Phosphorus applied before flooding was immobilized to a greater degree than when P was applied after draining a soil rich in organic carbon and reducible Fe. In soils low in organic carbon and reducible Fe, however, P applied before flooding was immobilized but P applied after drying was not (Willett, 1982).

Ru-kun *et al.*, (1982), however, found an increase of native P-availability to rice upon submerge followed by soil drying. He suggested that this may have resulted from organic P mineralization in soil, whereas, Fe-P- and Al-P-availability may have actually decreased.

Soil sorption capacity and bonding energy for P were increased upon flooding, and then further increased with drying. Drying also increased the amount of acid ammonium oxalate-extractable Fe and the Fe-bound P at the expense of Al-bound P. Consequently, flooding and drying were suggested to increase the activity of ferric hydrous oxides in sorbing P (by way of decreasing their crystallinity) that resulted in added P immobilization after draining the rice soils (Sanyal and De Datta, 1991).

Biological reduction of Fe during flooding, followed by reoxidation during drying, enhance reactivity of the sesquioxide fraction of the soil, consequently increasing the P-fixing capacity, and hence, decreased P solubility. Research results

suggest that the induced P deficiency in soils subjected to flooded-drained conditions was due to high P sorptivity and low P desorption as a consequence of Fe transformations in soil (Sah *et al.*, 1989).

Addition of organic matter and an elevated temperature greatly enhanced P sorption in drained soils from flooded-drained systems, thereby causing a higher P sorption for a relatively shorter period of previous flooding (Sah and Mikkelsen, 1989). The effect of organic matter was attributed to an increase of amorphous Fe in soil during the anaerobic decomposition of the organic matter as observed for soils under continuous flooding conditions (Sah and Mikkelsen, 1986b).

2. 4. Models for Estimating Extractable P or Residual Extractable P

Sri Adiningsih *et al* (1988) found that adding P fertilizer by 25%, 50%, 75% and 100% of the recommended rate of some soils of Java island, did not increase the net rice yield compared to that of the unfertilized. Therefore, increasing fertilizer-utilization efficiency is becoming a crucial factor in improving productivity of low fertility soils, especially after the enormous rise in fertilizer price on the world market. Consequently, knowledge of residual P and residual effects of P, and the appropriate means of quantifying them, is essential for efficient fertilizer utilization.

Russell (1977), developed a mathematical model to estimate efficient utilization of fertilizer, which included a mechanistic model. This model developed based upon the model in Figure 1. The behaviour of nutrients applied to soils was

expressed as mechanistic model, which could be used to predict residual effect of P. This mechanistic model comprises of two differential equations:

$$\frac{dA}{dt} = F(t) + K_3 U - (K_1 + K_2)A - P(t)$$

$$\frac{dU}{dt} = K_1 A - K_3 U$$

where A and U are the available and unavailable soil nutrient levels, and K_1, K_2, and K_3 are the fixation, loss and release coefficients respectively. $F(t)$ is the applied nutrient, $P(t)$ is the nutrient removed in harvested plant products.

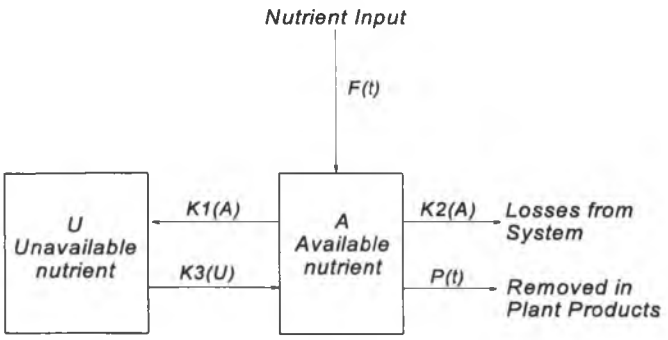


Figure 1. Diagram of nutrient dynamics of Russell's model.

Barrow and Carter (1978) modified Russell's model by slightly changing the right hand side of the model in Figure 1. Their model diagram is in Figure 2, and

modelled the losses of phosphate, and phosphate converted to organic forms by using a curvilinear relation such that the proportion lost or converted was high at low levels of application. This suggested that effectiveness of low levels of application declined relatively more quickly than for high levels of application.

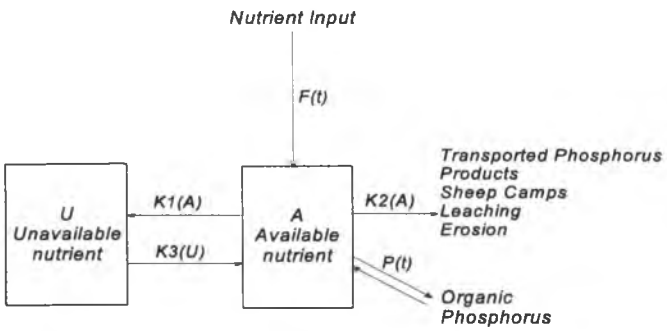


Figure 2. Diagram of phosphorus dynamics of Barrow & Carter's model.

Both Russell's, and Barrow and Carter's models did not specifically relate their equation models with the soil properties responsible for nutrient sorption and desorption. In addition, they did not incorporate the effect of plant growth in their models which had been hypothesized to have significant effects on P sorption and desorption.

Cox, *et al.* (1981), denoted that a problem encountered with mechanistic models is that they deal with changes in the level of biologically available nutrient with time. This level may be determined, if response data is handy, by extrapolation

or by some other predictive system. It cannot, however, be measured directly at any point in time. Descriptive models, on the other hand, may be based on the chemically extractable level of a nutrient.

Cox, *et al.*(1981) then developed a descriptive model that describes the change in an extractable-nutrient level with time as equal to a loss constant times the difference between that level and an equilibrium level.

This expression is as follows:

$$dX/dt = -k\,(X - X_{eq})$$

where X is the extractable-nutrient level (kg/ha); t is the time (years); k is the loss constant ($year^{-1}$); and X_{eq} is the equilibrium level of X (kg/ha).

Integration of the above equation and assuming that at time zero $X = X_{init}$, gave the following relationship:

$$X = X_{eq} + (X_{init} - X_{eq})\,e^{(-kt)}$$

where X_{init} is the initial level of X in kg/ha following the initial rapid sorption of added nutrient; the value of X_{eq} for a particular soil is undoubtedly a function of soil properties, crops grown, and climatic conditions. This value is usually unknown, and must be assumed from experience. While X_{init} is estimated by using the quadratic relationship between X_{init} and the rate of fertilization in kg/ha, as follows:

$$X_{init} = X_0 + b_1F + b_2F^2$$

where X_0 is the predicted level of extractable nutrient of the check plot, F is the fertilizer rate, and b_1 and b_2 are regression coefficients.

Lins, *et al.* (1985) modified Cox, *et al.*'s model by modifying the X_{init} equation by the following model:

$$X_{init} = X_i + (b_1 + E)*F + b_2*F^2$$

where X_i is the selected initial P concentration; and E is calculated as follows:

$$E = -b_1 + \sqrt{[b_1^2 - 4b_2(X_0 - X_i)]}$$

Both the Lins, *et al.* and Cox, *et al.*'s models are able to estimate the amount of residual P in soil, by subtracting the total P with the calculated X. These models, however, do not estimate the residual effect of P. Moreover, these models do not explicitly relate the estimation of extractable soil P with the soil properties, nor with the plant growth effect.

Matar (1989) further improved the Cox *et al.* (1981) and Lins *et al.* (1985) models. The significant difference between Matar's model and the previous two models is that the change in the extractable P in soils with time was considered to be related primarily to losses due to crop uptake and immobilization. Matar also assumed that the relationship between extractable P at time zero and the rate of fertilizer applied was linear. Therefore, Matar's final equation is:

$$P_t = P_{eq} + [(A+BF) - P_{eq}]\ e^{(-k1*t)} - TPU$$

where P_t the extractable P at any one time (kg/ha); P_{eq} is extractable P at equilibrium; A and B are the regression coefficients; k1 is the loss constant per unit time (P immobilization in soil); and TPU is the total P uptake from soil by crop in mg/kg. TPU is estimated by the equation:

$$TPU = (k2)P_0 e^{(-k2*t)}$$

where k2 is the rate of P uptake by crop per unit time.

However, like the previous two models, Matar's model did not relate the extractable P estimation to soil properties nor to estimate the residual effect of P.

Wolf *et al.* (1987), and Janssen and Wolf (1988), however, developed a simple equation for calculating the residual effect of phosphorus fertilizer. Their models were based upon the model structure of P as follows (Figure 3.):

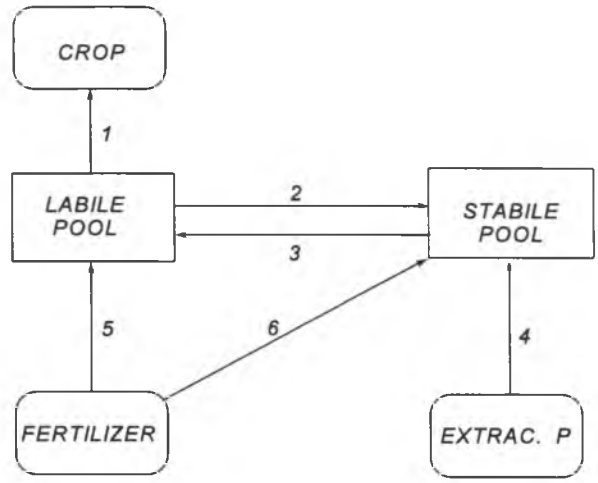


Figure 3. Diagram of phosphorus dynamics of Janssen & Wolf's model.

Their models were designed to estimate the residual P and the residual effect of P. Some deficiencies of these models were that they included several assumptions and constant parameters based upon previous experiences, and did not explicitly relate the estimation of residual effect of P with the soil properties.

CHAPTER 3. MATERIALS AND METHODS

The study area of this research was the island of Java, Indonesia. Ideally, this study should be conducted at several on-farm sites areas on this island, covering as many soil series as possible, and performed simultaneously. Without a tremendous amount of financial support, labor and facilities, however, such a study would be almost impossible to implement.

Plants most likely take up nutrients more effectively under a closed system of a pot experiment compare to that of the field condition. This indicates that an experiment assessing fertilizer recommendation performed as pot experiment will provide conservative results. Therefore it was preferable to conduct this study as a greenhouse experiment which employed ten soils representing ten locations of paddy soils in Java.

3. 1. The Island of Java, Indonesia

Indonesia is an extensive archipelagic country extending 5120 kilometers from east to west and 1760 kilometers from north to south. It encompasses 13667 islands, but only approximately 6000 are inhabited (U.S. Department of the Army, 1994). The island of Java is the smallest island among the five largest islands of the Indonesia archipelago, the others are Sumatra, Kalimantan, Sulawesi, and Irian Jaya, It extends between 105° to 115° East longitude and 5°50' to 8°45' South latitude.

Like Sumatra, and Kalimantan, Java island also lies in the Sunda Shelf --an extension of the Malay Peninsula and the Southeast Asian mainland (McNally, 1991).

Java was, and is, still the center of intensive rice cultivation on 'sawah' or paddy soil. This form of cultivation demands rich volcanic soils with a fairly low slope (nearly flat area) that permits water control. Java supplies most the rice of Indonesia and major food crops through intercropping on sawah and cultivation on unirrigated land (U.S. Department of the Army, 1994). According to Moersidi *et al.*, 1989; and Sri Rochayati *et al.*, 1990, the total area of sawah or paddy soil on Java and Madura is approximately 3653000 ha.

3. 2. Soil Samples

Based upon 25% HCl-extractable P, paddy soils on Java were classified into three classes, high (> 175 mg P kg^{-1}), medium (87.5 mg P kg^{-1}), and low (< 87.5 mg P kg^{-1}) 25% HCl-extractable P content (Moersidi *et al.*, 1989). In order to have soils that characterize paddy soils of Java, sampling locations were mapped in such way that the representative paddy soils encompassed not just all the soil P categories but also a wide range of soil properties affecting P sorption and availability.

The sampling locations were determined based upon the HCl-extractable P and soil classification information on the map of phosphate requirements of paddy soils (Pusat Penelitian Tanah dan Agroklimat, 1993). Soil samples that represented high, medium, and low HCl-extractable P were collected from East Java, Central Java, and West Java provinces. The latitude and longitude of sampling sites were

recorded by the use of a GPS (Global Positioning System) instrument (Table 1). The soil maps of East-, Central-, and West-Java along with the GPS recorded sampling locations are shown in Figures 4 to 6.

Soil samples were taken from the plow layer, at an approximate depth of 0-20 cm, and from the subsoil at the same sampling position but at a depth of 30-45 cm. Soils taken from 0-20 cm depth were used for the greenhouse experiment to study the change in residual extractable P using flooded rice as the indicator plant.

Table 1. Ten Representative paddy soils of Java, Indonesia

Sampling Location	GPS Reading Latitude/Longitude	Soil Order in:		Parent Materials
		Indonesian Classification[1)]	Soil Taxonomy Classification[2)]	
1. Serang, West Java	06°06.8720 S 106°14.9240 E	Gley Soils	Inceptisols	Deposited clay & sand
2. Cianjur, West Java	06°47.6363 S 107°09.8587 E	Latosols	Oxisols	Intermediate volcanic tuff
3. Kerawang, West Java	06°09.2493 S 107°24.1623 E	Alluvial Soils	Entisols/Inceptisols	Deposited clay
4. Brebes, Central Java	06°56.9045 S 109°02.8633 E	Alluvial Soils	Entisols/Inceptisols	Deposited clay
5. Purbalingga, Central Java	07°18.2889 S 109°24.3784 E	Grumusols/Mediterraneans/ Regosols	(?)	Limestone
6. Purwodadi, Central Java	07°07.6784 S 110°54.0315 E	Grumusols	Vertisols	Deposited clay
7. Madiun, East Java	07°41.8350 S 111°37.0440 E	Mediterraneans	Oxisols/Alfisols	Intermediate volcanic tuff
8. Mojokerto, East Java	07°30.8002 S 112°28.4114 E	Regosols/Litosols	Entisols	Intermediate to basic volcanic sand and dust
9. Silo, East Java	08°14.4778 S 113°50.6229 E	Regosols	Entisols	Intermediate to basic sand-dust & volcanic tuff
10. Jenggawah, East Java	08°14.2364 S 113°39.3644 E	Latosols/Litosols	(?)	Acidic, intermediate to basic volcanic tuff

[1)] Taken from Pusat Penelitian Tanah (CSAR), 1966.

[2)] The equivalent to Soil Taxonomy order taken from Supriyo, *et al.*, 1992.

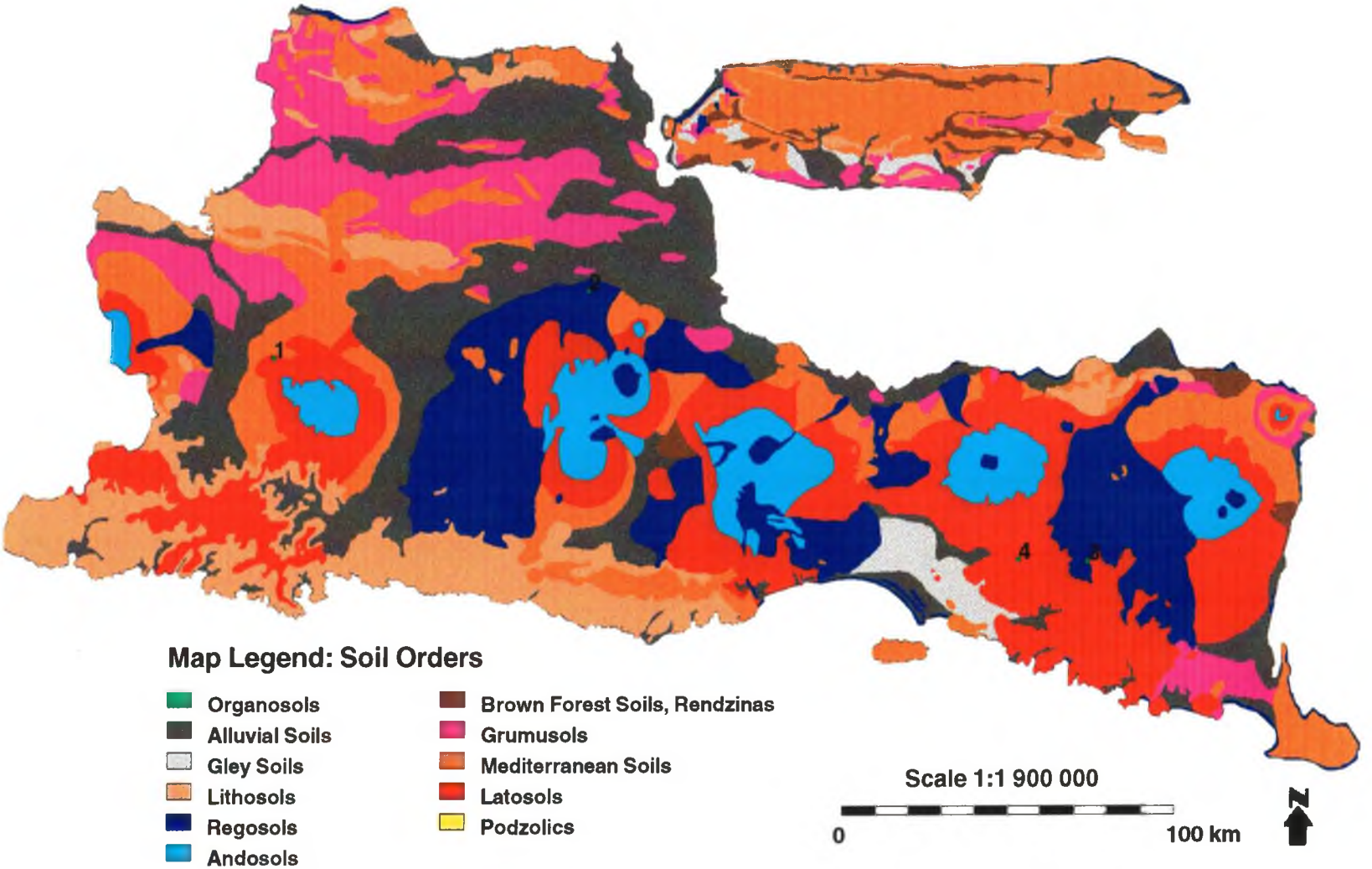


Figure 4. Soil map of East Java (Indonesian Classification System)
(111°20'-114°40' East Longitude and 6°40-8°45' South Latitude).

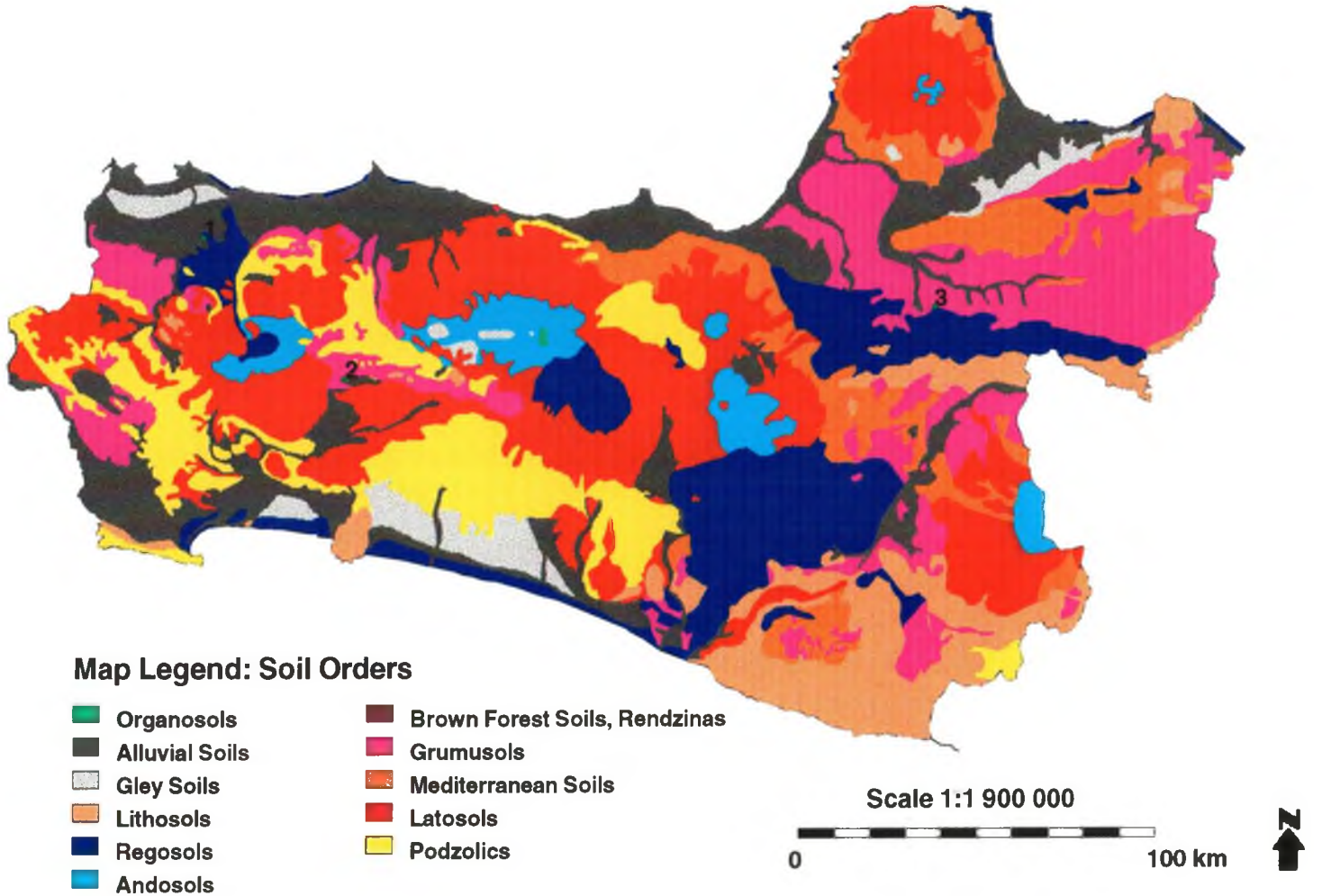


Figure 5. Soil map of Central Java (Indonesian Classification System) (108°40'–111°40 East Longitude and 6°40'–8°20' South Latitude).

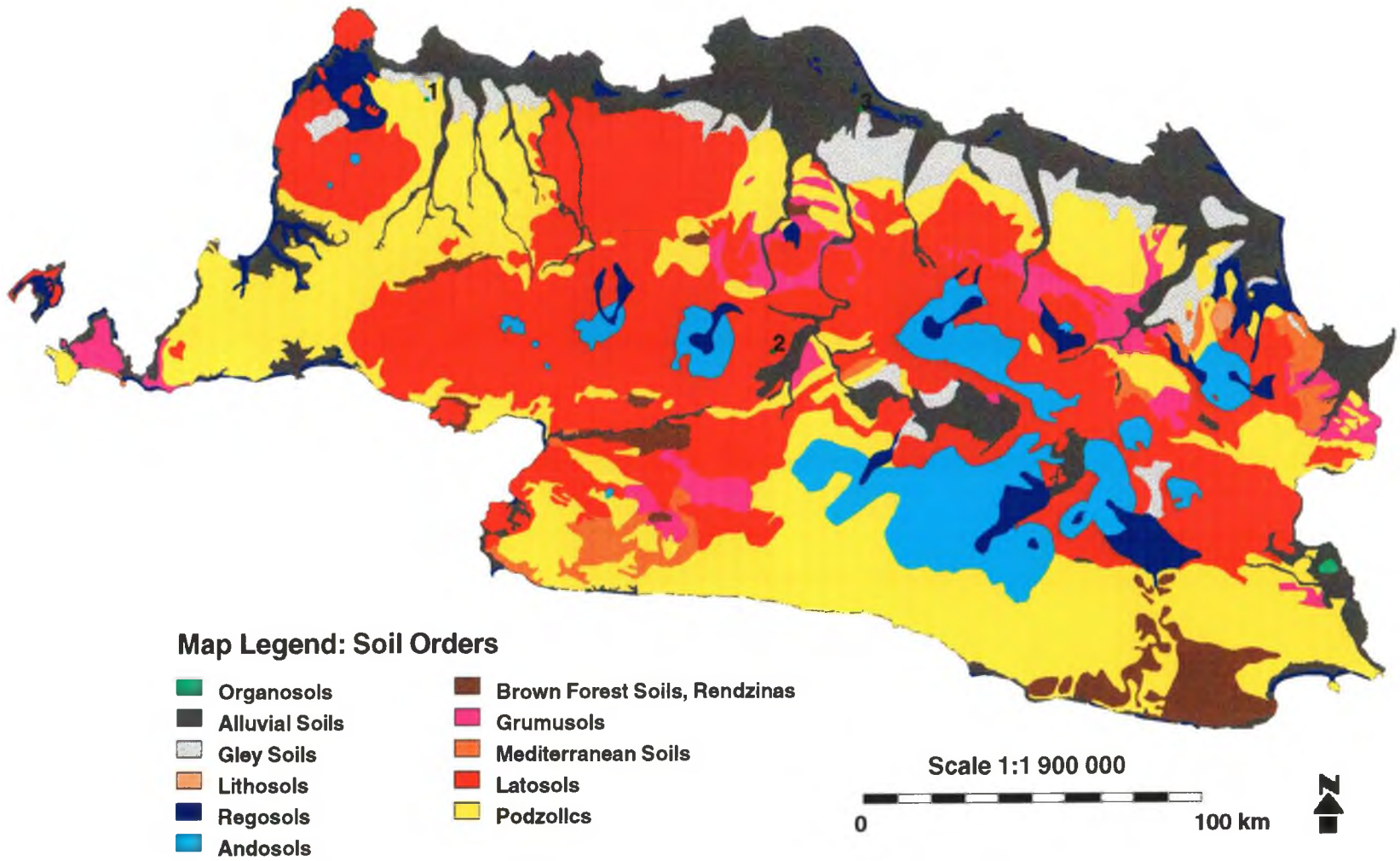


Figure 6. Soil map of West Java (Indonesian Classification System) (105°–108°40' East Longitude and 6°–7°40' South Latitude).

3. 2. Soil Characterization

Soil samples from the surface layer of 0-20 cm depth were air-dried and ground to pass a 2 mm sieve, and analyzed for soil properties known to affect P sorption and P availability in soils.

Soil samples from the subsoil (30-45 cm) were also air-dried and analyzed for some supporting measurements, which included soil pH and extractable soil P.

3. 2. 1. Chemical Properties

Soil pH was measured in 1:1 soil:solution mixtures with two solutions, deionized water and in 1*M* KCl solution (McLean, 1982). Suspensions were thoroughly mixed and allowed to sit for 1 hour then the pH was measured using a Hanna Instrument (HI 8314) membrane pH-meter. The instrument was initially calibrated at pH 4.0 and pH 7.0 at 25 ^{0}C.

Total soil P content was determined by the digestion method using a mixture of concentrated sulfuric acid (H_2SO_4) and perchloric acid ($HClO_4$) (Soil Science Society of China, 1983). One g of finely ground soil sample (approximately 100 mesh) was placed into 125 mL Pyrex flasks and moistened with deionized water. Eight mL of concentrated H_2SO_4 and 1 mL of 69-72% $HClO_4$ were added and mixed thoroughly. This mixture was then digested at low temperature, about 60 to 70 °C, until the dark color of organic matter disappeared and the white fumes of $HClO_4$ disappeared. Then, the temperature was increased to boiling and maintained for 1 hour. If necessary a few additional drops of $HClO_4$ were added to wash down black

particles on the side of the flask. The total digestion process usually required about 120-150 minutes for strongly weathered soils. The digested mixture was cooled down and transferred into a 100 mL volumetric flask and brought to volume with deionized water.

The standard curve was prepared as follows. The standard solutions containing 0.0, 2.0, 4.0, 8.0, 12.0, 16.0, and 24.0 μg P were diluted into 25 mL volume by adding 4 mL reagent B and deionized water. These standard solutions contained 0.0, 0.08, 0.16, 0.32, 0.48, 0.64, and 0.96 μg P mL^{-1}.

Total elemental content was determined by X-Ray Fluorescence (XRF) on a Siemens SRS303 Wavelength Dispersive X-ray Fluorescence Analyzer. The clay fraction of soil samples was analyzed for major elements on fused glass disks prepared by standard petrographic methods. Clay samples weighing approximately 1.5000 g were weighed and heated to 900 ^{0}C for determination of loss on ignition. Two subsamples of 0.4500 ± 0.0045 g taken from the ignited samples were weighed and mixed with 2.9500 ± 0.0020 g of lithium tertraborate fusion mixture. The mixture was melted and swirled at 900 ^{0}C to 1000 ^{0}C and formed into a glass disk for analysis (T. Hulsebosch, 1995 personal communication).

Extractable soil P by 25% HCl is the standard method used to determine the extractable P in paddy soils by the Centre for Soil and Agroclimate Research, Bogor, Indonesia (Suranta *et al*, 1989). Ten mL of 25% HCl was added to 2.0 g of soil. (Note: If the soil contained calcium carbonate, $CaCO_3$, we added 0.25 mL of 37%

HCl for every 1% $CaCO_3$, and brought the solution to 10 mL with 25% HCl). This solution was shaken on a reciprocal shaker for 5 hours. The solution was then centrifuged at 10 000 rpm for 10 minutes to obtain clear solutions, and then diluted 20 times with deionized water.

The standard curve was prepared as follows. Aliquots of 0.0, 0.2, 0.4, 0.6, 0.8, and 1.0 mL of 10 mg P L^{-1} standard solution were diluted into 1 mL each by adding standard solution of 0 mg P L^{-1}. Ten mL molybdate blue mixture were added and the solution left to equilibrate for at least 30 minutes.

Extractable soil P by 0.5*M* $NaHCO_3$ extractant was determined using 0.5*M* Sodium bicarbonate ($NaHCO_3$) at pH 8.5 (Suranta *et al*, 1989). Soil samples of 2.5 g were weighed and placed into 100 mL Erlenmeyer flasks, then 50 mL of the extracting solution were added. The mixture was shaken for 30 min on a reciprocal shaker. The suspensions were then centrifuged at 10 000 rpm for 10 minutes to obtain clear solutions.

The standard curve was prepared as follows. Aliquots of 0.0, 0.4, 0.8 1.0, 1.2, 1.6 and 2 mL of 5 mg L^{-1} P standard solution were brought to 2 mL volume each with the $NaHCO_3$ extracting solution. Ten mL molybdate blue mixture were added, and the solution allowed to equilibrate for at least 30 minutes.

Phosphate concentrations in all analyses (total soil P, 25% HCl-extractable P, and 0.5*M* $NaHCO_3$-extractable P), were measured with the ammonium molybdate reagent with ascorbic acid according to Murphy and Riley (1962) as modified by

Watanabe and Olsen (1965). Absorbance readings were determined using a Hitachi spectrophoto-meter model 100-40 with the wave length set at 882 nm for the total P analysis; while for the 25% HCl and 0.5*M* $NaHCO_3$-extractable P, P measurement were done by colorimeter using 1 cm cuvette and the filter was set at 693 nm.

> [Note: Reagent B was prepared by dissolving 1.056 g of ascorbic acid in 200 mL of reagent A, and mix. Reagent A was ammonium paramolybdate $[(NH_4)_6Mo_7O_{24}\cdot 4H_2O]$, which was prepared by dissolving 12.0 g of ammonium paramolybdate in 250 mL of deionized water; and potassium antimony tartrate ($KSbO\cdot C_4H_4O_6$) of 0.2908 g dissolved in 100 mL of deionized water. Both dissolved reagents were transferred into 1 liter of 2.5*M* H_2SO_4, mixed thoroughly, and made to volume with deionized water to 2 liters].

Acid ammonium oxalate-extractable Iron and Aluminum was determined to estimate the amount of amorphous iron (Fe) and aluminum (Al) hydrous oxides in the soil (Suranta *et al*, 1989). Soil samples of 1.0 g were weighed and mixed with 50 mL of 0.2*M* acid ammonium oxalate extraction at pH 3 in a centrifuge tube wrapped in aluminum foil to prevent light from altering the reaction with hydrous oxides, and then shaken four hours. Thirty-five mL of this suspension was transferred into centrifuge tubes and 3-4 drops of acetone 99% A.C.S. reagent were added and the mixture was shaken, and centrifuged. Iron, and Al concentrations were determined in the oxalate supernatant by Atomic Absorption Spectrophotometer using the acetylene-air flame, while for Al a nitrous oxide-acetylene flame was used.

Organic Carbon content was determined by a modified Walkley-Black procedure (Suranta *et al*, 1989). Soil samples of 0.50 g were weighed, and mixed

with 7.5 mL of concentrated H_2SO_4 and 5 mL of 1*M* $K_2Cr_2O_7$. This mixture was heated on a water bed heater for 1.5 hours, cooled and diluted to 100 mL with deionized water, and shaken until the solution became clear. Twenty mL of the solution was pipetted into a 250 mL Erlenmeyer flask, and 2 mL of concentrated H_3PO_4 and 5 drops of 0.16% barium diphenylamine sulphonate were added. The mixture was titrated with 0.2*M* ferrous sulfate heptahydrate ($FeSO_4 \cdot 7H_2O$). A blank without soil was prepared in the same manner. The organic C content was then calculated as:

$$\% \text{ Organic C} = (V_1 - V_2) \times M \times 3 \times FK,$$

where, V_1, and V_2 are the amount of ferrous sulfate heptahydrate used in the titration of the sample solution and blank respectively; M is the molarity of ferrous sulfate heptahydrate; and FK is the moisture content correction factor.

Calcium Carbonate content was determined by the Scheibler method (Suranta *et al*, 1989). Soil samples weighing between 0.25 to 2.5 g were placed in a 30 mL plastic cup inside shaker bottles of the Scheibler apparatus, which were previously filled with 10 mL of 10% HCl. A standard was prepared by weighing 0.250 g $CaCO_3$ reagent grade, and the blank was prepared without soil. The bottles were then shaken for 15 minutes, and the amount of CO_2 gas formed was recorded. The % $CaCO_3$ concentration was calculated as:

$$\% \text{ CaCO}_3 = \{(B-C) \times 25 \times FK\} / \{(A-C) \times G\},$$

where, A, B, and C are the amount of CO_2 gas formed by the standard $CaCO_3$, soil

sample, and the blank respectively; G is the weight of soil sample in gram; and FK is the moisture content correction factor.

3. 2. 2. Physical Soil Properties Analyses

Soil Texture was determined by the pipette method for all soils (Suranta *et al*, 1989). The pipette method is often used as a standard method from which other particle size analysis methods are compared.

A ten gram sample of soil was mixed and boiled with H_2O_2 to remove the organic matter, and then mixed with 200 mL HCl 0.1*M* to remove the $CaCO_3$. The organic matter and $CaCO_3$ free soil sample was then dispersed with 10 mL 4% Na-pyrophosphate. The dispersed soil suspension was then sieved through a 50 micron sieve into a sedimentation cylinder to separate the sand. The total solution volume was brought to 500 mL. To determine the amount of silt, the silt and clay suspension was shaken thoroughly and left to settle for one minute and was sampled at a 10 cm depth by pipette. To determine the amount of clay, the silt and clay suspension was shaken completely and left to settle for 3.5 hours and sampled at a 5.2 cm depth by pipette allowing enough time for all silt to settle below the 5.2 cm sampling depth. Twenty mL aliquots were drawn by pipette then oven dried at 105 ^{0}C to determine the amount of clay.

15-bar water content was determined using the pressure chamber procedure (Richards, 1965). The undisturbed soil samples were placed in the pressure chamber, then saturated with deionized water for 2-3 hours before the 15 bars of pressure was

applied to the chamber. The moisture content of the soil samples was determined after at least 24 hours of pressure application.

Surface area was calculated from glycerol retention according to the method of Diamond and Kinter (1958). A 0.200 g sample of soil was weighed onto a pre-weighed aluminum dish, oven-dried at 110 ^{0}C (about 2 hours) to a constant weight, cooled and weighed within the next 30 seconds on an analytical balance. The soil was saturated with 5 mL 2% glycerol solution and swirled gently to mix and distribute the mixture evenly. The specimen was then oven dried at 110 ^{0}C in the presence of glycerol vapors to a constant weight. The area of glycerol film was calculated by Diamond and Kinter (1958) as follows:

Area of glycerol layer = Volume/Thickness
= 0.794 cm^3 / $4.5x10^{-8}$ cm
= 1765 m^2

Thus, a glycerol retention of 1% would be equivalent to a monolayer area of 17.65 m^2/g; however, since the layer of glycerol molecules is between two basal surfaces of the clay, the internal clay surface covered by the monolayer is twice the area of the monolayer, or = 35.3 m^2/g.

Clay physical activity is defined as the ratio of the plasticity index to percent clay (Skempton, 1953). The plasticity index is the difference between liquid limit and plastic limit, or the moisture content range over which a soil material is in a plastic state. The liquid limit is an estimate of the minimum moisture content at which the soil exhibits a tendency to undergo liquid flow turning from a viscous to a

plastic state. The plastic limit roughly approximates the minimum moisture content at which a soil may undergo deformation without rupturing (Uehara and Gillman, 1981).

Liquid limit was determined by using the liquid limit device, which was filled about two-thirds full with wet fairly stiff soil paste. The soil surface was smoothed off with a spatula so that the maximum depth of the soil was about 1.27 cm (parallel to the base of the machine). Using the grooving tool, a groove was drawn through the soil across the center of the soil mass. The crank of the machine was turned at a rate of two blows per second. The liquid limit was attained when the groove closed over a length of 1.27 cm with 25 blows of the machine. The moisture content of soil along the groove was then determined.

[Note: Two alternatives to this procedure can be used,

1. If more than 25 blows close the groove, then we may draw a graph of moisture content versus the number of blows. Then use the 25 blow moisture content for the liquid limit.
2. Soil engineers employ the equation:
   $W_{LL} = W_N (N/25)^{0.121}$
   where: W_{LL} = moisture content at liquid limit
   W_N = moisture content at N blows
   N = number of blows (this must be between 18 and 32)

(Sowers, 1965).]

The plastic limit was determined by preparing soil paste so that the soil could be rolled into a stiff ball, which was then kneaded and thoroughly mixed by hand. A portion of soil was removed and rolled on a glass plate by hand, if the soil could be rolled into a thin wire about 1/8 inch in diameter and in so doing broke into pieces

1.27 cm long, the soil was at the plastic limit. The moisture content at plastic limit was determined.

Plasticity index was calculated by taking the difference between liquid limit and plastic limit (Sowers, 1965).

Soil Mineralogy was examined by X-ray diffraction analysis of the clay fraction for all soils. The sand fraction was separated from the silt and clay fraction by wet sieved through a 45 μm sieve then dried and ground to pass through 75 μm sieve. The clay fraction was separated from the (clay + silt) suspensions by dispersing the suspensions using 0.1*M* Li(OH) or Na(OH), followed by centrifugation as well as ultracentrifugation of the supernatant.

The air-dried clay samples were packed randomly into bulk powder mounts and analyzed on a Phillips Scientific Instruments XRG 3100 diffractometer using a Co X ray tube operated at 40 kV and 25 mA. The samples were analyzed with a 4-second integration time at 0.025 2Θ steps without a theta-compensating divergence slit for the range of 4 to 76 degrees 2Θ. Count data were recorded on computer disk for plotting and further processing.

3. 3. Plant Analysis

The purpose of plant analysis was to measure the amount of soil P that was taken up by the rice plant. This quantity was particularly important in relation to determining the desorption of the residual P (of the residual pool) (Figure 7.) that replenishes extractable P.

The rice plants were harvested and analyzed for phosphorus concentration at 8 weeks after planting. Phosphorus concentrations were measured in both the above ground portion (the leaves and stems) and the under ground portion(the roots).

Plant P content was determined by the wet destruction procedure with a mixture of 65% p.a. HNO_3 and 60% p.a. $HClO_4$ (Sudjadi and Suranta, 1983). Approximately 0.250 g of plant sample was weighed and mixed with 3.5 mL HNO_3 and 0.5 mL $HClO_4$. This mixture was allowed to equilibrate for 20 hours, and heated at 150 ^{0}C for 90 minutes then the temperature was raised to 200 ^{0}C until the amount of residue left was approximately 0.5 mL. This residue was then diluted to 50 mL. Phosphate concentration was measured by spectrophotometer using the Murphy-Riley procedure with the absorbance set at 693 nm.

All analyses were conducted at Center for Soil and Agroclimate Research (Pusat Penelitian Tanah dan Agroklimat) Bogor, except for the X-ray Diffraction analysis, XRF total elemental analysis, and the total P analysis, which were completed at the Department of Agronomy and Soil Science, University of Hawai'i at Manoa.

3. 4. Greenhouse Experiment

The main objectives of the greenhouse experiment were: 1. to measure the amount of P taken up by rice plants during the growing season; 2. to measure the amount of P sorbed by the soil matrix per unit time (adsorption rate); 3. to measure the amount of residual P that can become extractable P per unit time (desorption rate);

and 4. to determine the relationship of adsorption and desorption with the related soil properties

There were two greenhouse pot paired-experiments which were conducted simultaneously in this study. One pot experiment was conducted with rice as the indicator plant, while the other was conducted without any plant.

The pot experiment was conducted at the greenhouse facilities of the Centre for Soil and Agroclimate Research, in Bogor, West Java, Indonesia. Five kg of each of the 10 soils was placed in plastic buckets of 13.23 liter size. Five rice plants of IR64 cultivar were transplanted in each pot for the experiment with rice.

Fertilizer applications were: **a.** Nitrogen fertilizer given as a total of 250 kg ha^{-1} Urea 99.5% A.C.S. reagent, ½ applied one day before planting and ½ at 4 weeks after planting; **b.** Potassium fertilizer given as 100 kg ha^{-1} potassium chloride (KCl) 99.5% A.C.S. reagent, applied once one day before planting; and **c.** Phosphorus fertilizer given as 0, 20, and 40 kg P ha^{-1} as phosphoric acid (H_3PO_4) 85% A.C.S. reagent, applied one day before planting of the first crop.

3. 4. 1. Pot Experiment with Rice Plant

This experiment was carried out as a two factor factorial selection of treatments utilizing a Randomized Complete Block Design (RCBD) with 2 replicates. The first factor was soils (ten soils), and the second factor was the application rate of P fertilizer, 0, 20, and 40 kg P ha^{-1}, applied as phosphoric acid (H_3PO_4). The rate of P

fertilizer was selected to correspond with the amount of P fertilizer recommended by the Indonesian government in this case is the Ministry of Agriculture..

The experiment was continued for four crops, with 4 weeks intervals between each crop. Fertilizer P was applied only to the first crop. Each crop was harvested at 8 weeks after transplanting, which is approximately the stage of maximum tiller number. Extractable and total soil P as well as plant P content were measured at planting and harvesting of each crop.

3. 4. 2. Pot Experiment without Rice

The purpose of the second pot experiment was to measure the adsorption and desorption of P in some soils without the influence of plant growth. The experiment was carried out under the same conditions and at the same time as the first pot experiment, except without rice plants.

3. 5. Developing Prediction Models for the Change in Residual Extractable P

Paddy soils in Java, have been intensively fertilized with phosphorus (in the form of TSP) for at least three decades through government subsidized intensification packets to the farmers. This centralized decision making, however, has had some unfortunate side effects. One effect has been the growing imbalance of nutrients in paddy soils, and especially of phosphorus in paddy soils of Java, which in some cases have led to excessive levels.

Increasing fertilizer-utilization efficiency is therefore becoming a crucial factor in improving productivity of low fertility soils, and maintaining the nutrient balance and crop productivity.

Phosphorus recommendations cannot be generalized to all soils. They must be specific for specific soils. Therefore, there was a need to develop a model that uses soil testing and crop information to predict the change of residual extractable P on paddy soils. Such a model could be applied to generate site specific recommendations to improve on the present strategy which is one recommendation for all soils.

The purpose of developing such a model was to predict the change in residual extractable P of a given soil at any time using frequently and easily measured soil properties that affect P sorption behavior in soil. So that the model can be widely applicable at low cost with minimum effort. Such soil properties are clay content, soil pH, organic carbon content, $CaCO_3$ content, Fe and Al content, initial extractable P, and clay physical activity.

In the present study residual extractable P refers to that P measured as soil extractable P left over from previous fertilization but available to successive crops. Figure 7 illustrates the soil-plant P dynamics in soil. The term extractable P and residual extractable P refer to the same pool from which plants absorb P. While, the residual P or non-extracted P pool refers to the quantity of P which is not extracted at a given time, but might be at some other time.

The algorithm used for predicting residual extractable P with respect to time was based on the decline in soil P illustrated in Figure 8. The plot representing the change in extractable or residual extractable P with the influence of crop uptake with time. While the residual P or the non-extracted P pool is illustrated below.

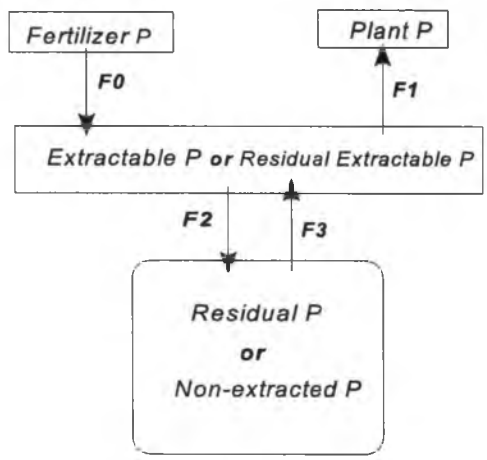


Figure 7. The diagram of phosphorus behavior in soil.

There were two assumptions attached to the concept illustrated in Figure 7. First, that P fertilizer contributed directly to extractable P pool. Second, plants uptake occurred only from extractable P pool.

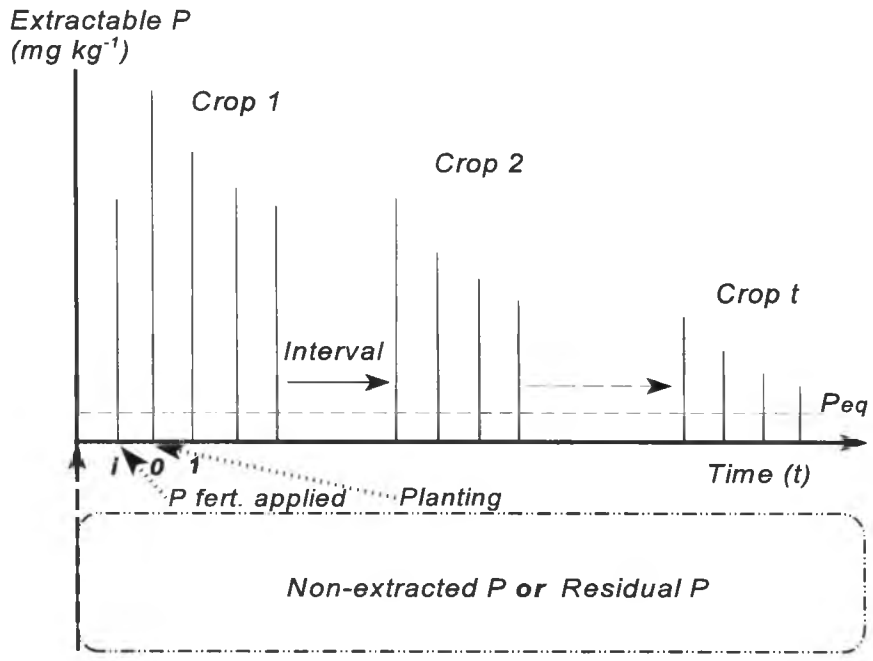


Figure 8. Illustrative model for predicting change in extractable P.

The amount of extractable P (residual extractable P) at any time t (where t = 1, 2, ... weeks), EP_t, was estimated with a nonlinear exponential model, which was similar to the basic nonlinear equation used by Cox *et al*, (1981) and Lins *et al*, (1985), as follows:

$$EP_t = EP_0 + b \exp(-k \ time) \qquad [1]$$

where, EP_t is the extractable P measured at time t, EP_0 is the extractable P at planting of the first crop following P fertilization, b is coefficient and k is loss constant. EP_0 is a function of the initial extractable P in soil (EP_i) and the applied P fertilizer. Therefore, the equation [1] can be modified as :

$$EP_t = EP_i + b_1 P + b_2 \exp(-k \ time) \quad [2]$$

where, P is the amount of applied P fertilizer (in kg of P ha^{-1}), b_1 and b_2 are the model coefficients, k is the loss constant of P caused by the sorption of P by the soil.

Equation [2] is a general equation that does not include individual soil properties as variables. This requires that different soil be assigned different parameter values in equation [2]. Site specificity can be described by incorporating soil variables to replace each coefficient in equation [2]. Then, equation [2] is expanded to:

$$EP_t = (a\, EP_i - P_{eq}) + f(\text{soil properties})\, P + f(\text{soil properties}) \exp\{-f(\text{soil properties})\ time\} \quad [3]$$

where, **a** is a coefficient, and P_{eq} is the equilibrium value of P in soil, which is the value that the system began with and will ultimately reach if P applications cease but production continues (Cox *et al*, 1981; Jackman, 1994).

Equation [3] would be fitted to measured extractable P obtained from both experiments with and without rice crops. Therefore, the term of P uptake by plant was not included explicitly but implicitly in the equation.

3. 6. Developing Prediction Models for Desorption from Residual P to Residual Extractable P

The desorption of residual P is defined as the movement of P from the residual P pool to the extractable P pool. When soluble P is added to a soil, any pre-existing P equilibrium will be disturbed, and there will be a movement of extractable P to the adsorbed form (non-extracted P or residual P pool) (F2 downward arrow of Figure 7).

When P is removed from the extractable P pool, for example by plants, there will tend to be a counter movement of P from the residual pool (F3 upward arrow of Figure 7).

The purpose of developing a desorption P model was to predict the desorption rate of residual P that buffers the residual extractable P. There are two ways of measuring the P desorption rate based on the data obtained in this study. First, is the total desorption of P, which is desorption rate measured cumulatively from each crop. Second, is the net desorption, which is desorption rate measured individually at each crop

3. 6. 1. Total Desorption (TD)

Total desorption of P was measured as the difference between crop uptake P (CUP) with the difference between extractable P measured with and without rice crops, and it was measured cumulatively for the entire crops (see equation [4] below).

The amount of total desorption of residual P that supported extractable P at any time, t, where t = 1, 2, ... weeks, was denoted as TD_t and calculated as:

$$TD_t = CUP_t - (EP_t^{-C} - EP_t^{+C}) \quad [4],$$

where CUP_t is the cumulative amount of P taken up by the crop at time t, EP_t^{-C} is the extractable P at time t measured without rice crops do not exist, and EP_t^{+C} is the extractable P at time t measured with rice crops.

Similar to the principle for developing a model to predict residual extractable P, the model for predicting desorbed P should employ frequently and easily measured and inexpensive soil properties that influence P sorption-desorption in soils.

The TD_t model was estimated with a nonlinear exponential equation similar to the development of the nonlinear exponential equations [1] to [3] except that instead of using a negative exponential nonlinear equation this model used a positive exponential nonlinear equation.

Therefore, the general form of the TD_t equation is:

$$TD_t = EP_i + b_1 P + b_2 \exp(k \text{ time}) \quad [5]$$

where, P is the amount P fertilizer applied in kg of P ha^{-1}, b_1 and b_2 are model coefficients (constants), and k is the accumulation constant of P (from the view of the extractable P pool) caused by the desorption of residual P to extractable P.

Equation [5] above is then modified in such way so that it becomes specific for a given soil. This can be accomplished by incorporating soil variables to replace each of its parameters. Equation [5] is expanded to:

$$TD_t = (a\, EP_i - C_v) + f(\text{soil properties})\, P + f(\text{soil properties}) \exp\{+f(\text{soil properties})\ \text{time}\} \quad [6]$$

where, **a** is a coefficient of the model, and C_v is a constant value.

3. 6. 2. Net Desorption (ND)

Net desorption is denoted as ND and is actually the net desorption, which is calculated as the difference between desorption (F3) and adsorption (F2) (Figure 7) and measured at every crop.

The net desorption (ND) was measured by considering the change in extractable P of the extractable P pool (Figure 7) as the net results between flow-in and flow-out processes, and was expressed as:

$$d(EP)/dt = Flow_{in} - Flow_{out} \quad [7],$$

and by referring to P diagram of Figure 7., it can be expanded as:

$$d(EP)/dt = \{(F3\text{-}F2)_t + \mathbf{bc}\ FP\} - CUP_t \quad [8]$$

If dt is a crop unit time, d(EP)/dt can be simplified as $d(EP)_t$. Variable (F3-F2) is actually the net desorption (ND) occurring between the residual P and the extractable P pools at any crop. Equation [8] can be rewritten as:

$$d(EP)_t = ND_t + \mathbf{bc}\ FP - CUP_t \quad [9],$$

only variable ND_t in equation [9] is unknown, therefore it is calculated as:

$$ND_t = d(EP)_t + CUP_t - \mathbf{bc}\ FP_t \quad [10],$$

where $d(EP)_t$ is the change in extractable P from planting to harvest in any crop, t, CUP_t (F1 in Figure 7) is the plant P uptake at crop t, FP_t (F0 in Figure 7) is the amount of P fertilizer applied at crop t. (Note: *in this study the P fertilizer was applied only once, that was at one day before planting time of the first crop*), and **bc** is the "buffer coefficient" of the soil.

The calculated ND_t values were then estimated/modeled as a function of initial extractable P, amount of P applied, and soil properties by a nonlinear negative exponential equation. The general form of the ND_t equation is:

$$ND_t = EP_i + b_1 P + b_2 \exp\{-(k)\ time\} \quad [11],$$

where, P is the amount of P fertilizer applied in kg ha^{-1}, b_1 and b_2 are model coefficients, and k is a decay constant.

Equation [11] above is then modified in such way so that it becomes specific for a given soil. This can be achieved by incorporating soil variables to replace each parameters in equation [11]. Then, equation [11] is expanded to:

$$ND_t = (a\ EP_i) + f(\text{soil properties})\ P + f(\text{soil properties})\ \exp\{-f(\text{soil properties})\ \text{time}\} \quad [12],$$

where, **a** is a coefficient of the model.

3. 7. Statistical Analysis

The purposes of the statistical analysis were to: 1) identify soil properties that were significantly correlated with the change in extractable P over time, and 2) to fit a non linear regression with the data for the change in residual extractable P with time. Statistical analysis was performed using S-Plus® for WINDOWS® and UNIX®, and graphical presentations were prepared using either Sigma Plot® version 2.0 for WINDOWS® (Jandel Scientific, 1994) or QuattroPro® version 5.0 for WINDOWS® (Borland International Co., 1994).

The S-Plus function COR was used to examine the multiple correlation among the soil properties with the measured extractable P over time. The function NLS (Venables and Ripley, 1994) was used to fit the nonlinear negative exponential regression of the change in residual extractable P with time (equation [3]). NLS is a nonlinear regression function that searches for the parameter values that provides the

best fit of the model to the data points. *Best fit* was found by the set of parameters providing the least residual standard errors. The algorithm utilized to solve the nonlinear regression model was *plinear*, the Golub-Pereyra algorithm for partially linear least-squares models (Venables and Ripley, 1994).

There are two advantages in using the partially linear algorithm. First, it can be much more stable than methods that do not account for linear parameters. Second, it requires initial estimates for fewer parameters and it can often converge from poor starting positions where other procedures fail (Venables and Ripley, 1994).

Four to five soil variables mostly correlated with extractable P were selected to be included in the model. Likewise, three to four soil variables correlated with both total desorption and net desorption of residual P were also selected to be involved in the prediction model of desorbed residual P. Approximately 180 to 220 model combinations were tested using the NLS procedure. The model that had the smallest residual standard error was taken as the best model for predicting the change in extractable P.

The nonlinear curve fitting procedure of SigmaPlot® for Windows® (Jandel Scientific Software, 1994) and PROC NLIN of SAS® for UNIX® (SAS Institute, 1993) were also used to verify the results found by the NLS module of S-Plus®.

The fitted models were then graphed using SigmaPlot® for Windows® to examine the change in residual extractable P in contrast to the critical level of P over time.

3. 7. Geographical Information System (GIS) Analysis

The purpose of the GIS analysis was: 1) to map the initial extractable P of some areas besides the sampling areas; 2) to apply the prediction from the mathematical model developed from the statistical analysis to generate regional estimates beyond sampled areas; 3) to map the change in residual extractable P with respect to time.

The 1 m by 1.5 m soil maps of East-, Central-, and West-Java of 1 to 250 000 scale (Pusat Penelitian Tanah, 1966) were digitized into a computer format using ARC/INFO® software version 3.4.2b for PC (Environmental Systems Research Institute, Inc., 1994).

The digitizing was performed using a 1.11 m by 1.5 m HIPAD Plus 9200 series Houston Instrument digitizing tablet at the GIS laboratory of the East West Center - Program on Environment. The digitized map data were then cleaned using the CLEAN command and exported to the ARC/INFO® for Unix format for further analysis by the EXPORT command of the workstation ARC/INFO®. The exported maps were edited for the node errors, and unclosed polygons. Polygon labels were added by applying the ARCEDIT commands (ESRI, 1992) such as, editfeature-node, -arc, and -label. Since the original format of the maps was on latitude and longitude projection, it was reformatted into a UTM projection utilizing the PROJECT and TRANSFORM of the ARC commands. Likewise, the GPS recorded sampling sites were also transformed into UTM projection, then generated into point coverage by

the ARC command GENERATE (ESRI, 1992). The soil data were prepared using a spreadsheet software, QuattroPro®, and joined into the appropriate soil coverage utilizing the ARC command JOINITEM (ESRI, 1992). The developed model from equation [3] was then incorporated into the ARC Macro Language programming (ESRI, 1993), and the results of the predicted residual extractable P were displayed as maps.

CHAPTER 4. RESULTS AND DISCUSSION

4. 1. Characteristics of the Representative Soils

The purposes of initial measurement of some soil properties for each representative soil were: 1) to measure the initial values of some soil properties which were affecting the change in residual extractable P in soil, and 2) to measure the change in residual extractable P in soils after the addition of P fertilizer and after several crops of rice.

The initial chemical properties are shown in Tables 2a & 2b, and some physical properties of the soils are shown in Tables 3a & 3b.

Table 2a. The initial chemical properties of the representative soils.

Soils	NH_4-Oxalate Fe	Al	Organic C	$CaCO_3$
	----------	----------	g kg^{-1}	----------
Serang	0.163	0.782	14.9	1.0
Cianjur	0.487	2.236	19.5	1.0
Kerawang	0.447	2.171	17.2	1.0
Brebes	0.175	0.787	13.0	1.1
Purbalingga	0.475	2.410	16.4	1.3
Purwodadi	0.138	0.669	13.9	125.0
Madiun	0.401	2.032	16.9	1.0
Mojokerto	0.222	1.745	9.6	0.3
Silo	0.404	1.856	24.2	1.0
Jenggawah	0.131	0.585	28.8	1.3

Table 2b. The initial chemical properties of the representative soils.

Soils	pH H_2O	pH KCl	HCl-P	0.5*M* $NaHCO_3$-P	Total P
			---------- mg kg^{-1} ----------		
Serang	4.88	4.48	83[†]	11.8[#]	173
Cianjur	4.73	4.24	507[§]	13.5[#]	701
Kerawang	4.54	3.95	170[‡]	29.7[#]	392
Brebes	6.24	5.41	240[§]	10.5[¶]	456
Purbalingga	4.75	3.98	188[§]	23.6[#]	370
Purwodadi	7.43	6.58	633[§]	11.4[#]	748
Madiun	5.62	5.01	383[§]	22.3[#]	646
Mojokerto	6.00	5.19	127[‡]	38.9[#]	293
Silo	6.04	5.19	310[§]	8.7[¶]	743
Jenggawah	6.21	5.42	275[§]	20.1[#]	642

[†]) Low initial HCl-P; [‡]) Medium initial HCl-P; [§]) High initial HCl-P
[¶]) Medium initial 0.5*M* $NaHCO_3$-P; [#]) High initial 0.5*M* $NaHCO_3$-P.

Table 3a. Some initial physical properties of the representative soils.

Soils	B.D.	Sand	Silt	Clay
	Mg m^{-3}	---------- % ----------		
Serang	1.15	31.0	50.0	19.0
Cianjur	0.85	7.0	39.0	54.0
Kerawang	0.86	2.0	34.0	64.0
Brebes	1.14	11.0	39.0	50.0
Purbalingga	0.98	4.0	23.0	73.0
Purwodadi	1.40	2.0	15.0	83.0
Madiun	1.02	10.0	28.0	62.0
Mojokerto	1.45	41.0	38.0	21.0
Silo	0.81	31.0	38.0	31.0
Jenggawah	1.01	20.0	45.0	35.0

Table 3b. Some initial physical properties of the representative soils.

Soils	Surface Area	15 MPa Moist. Cont.	Plasticity Index	Clay Physical Activity†
	-- m^2g^{-1} --	-- % --		
Serang	8.6	10.9	15.4	0.81
Cianjur	51.8	29.2	28.3	0.52
Kerawang	74.5	31.1	46.8	0.73
Brebes	83.7	32.9	38.3	0.77
Purbalingga	107.5	38.7	49.9	0.68
Purwodadi	100.6	36.0	44.7	0.54
Madiun	39.1	29.0	33.5	0.54
Mojokerto	29.3	26.0	14.4	0.69
Silo	65.9	13.5	24.0	0.77
Jenggawah	75.6	26.9	27.6	0.79

†) Clay physical activity was measured as a ratio of plasticity index to percent clay.

The total elemental analyses, X-Ray Fluorescence (XRF) procedure, of the clay fraction of representative soils are shown in Tables 4a & 4b. While the results of the X-Ray Diffraction analyses are shown in Figures 9a & 9b to 13a & 13b.

The above soil chemical and physical properties indicate that there was a wide range in soils utilized for this research. This was planned so that the model developed from this study can be applied to a very wide range of soils, and hopefully to predominantly the inorganic soils.

The representative soils included only one soil low in HCl-extractable P and none low in 0.5*M* $NaHCO_3$-extractable P. These were actually beyond what was originally planned (Table 2b). The sampling locations were planned based on the

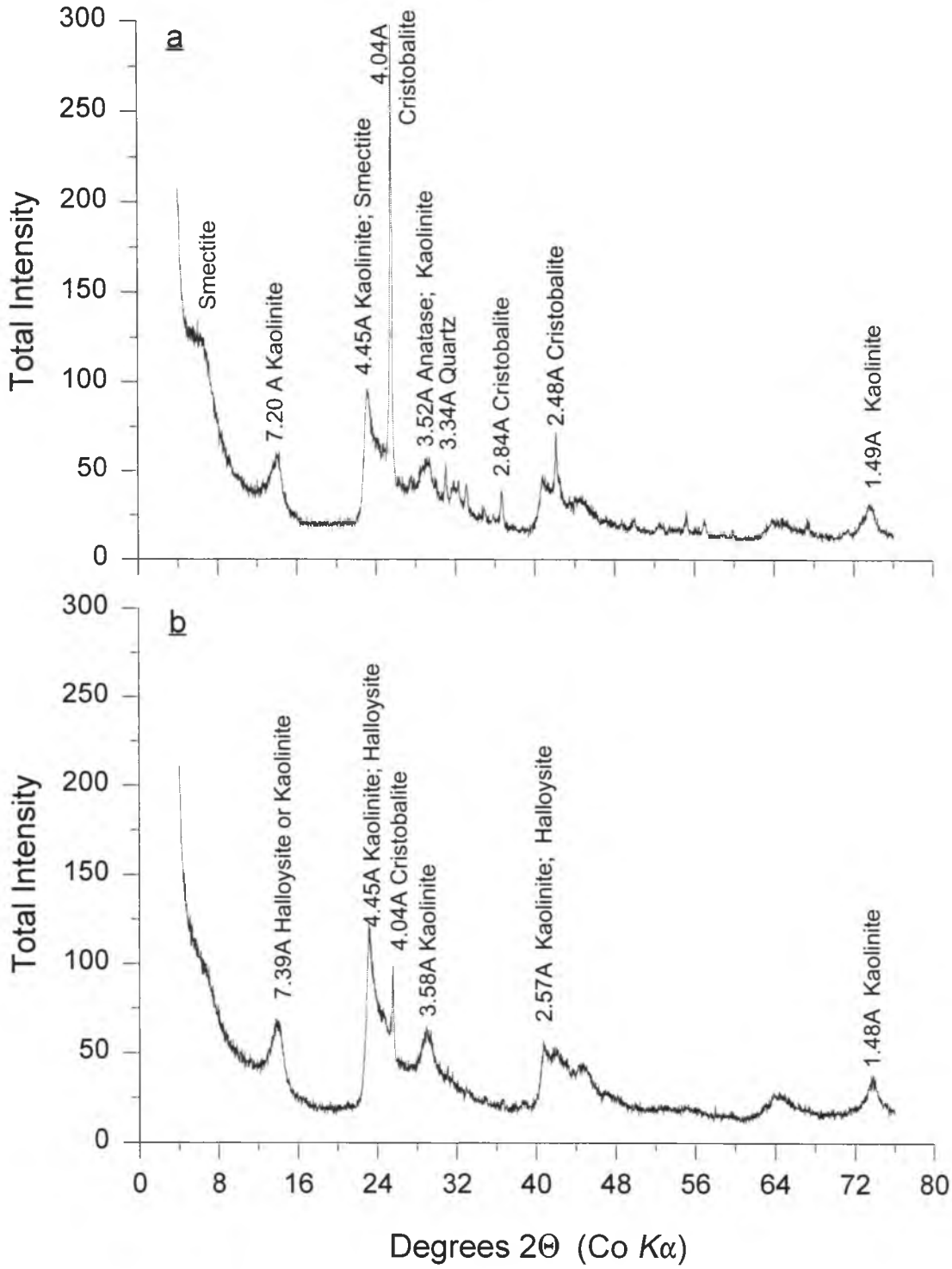
maps of HCl-extractable P status of Java paddy soils of 1988 to include all the three categories for each province. Presumably, there would include three soils had low HCl-extractable P, four soils had medium HCl-extractable P, and three soils had high HCl-extractable P. However, after the soils were collected, the initial values of the HCl-extractable P showed differently, which was only one soil had low HCl-extractable P. This indicated that there was a fast change in accumulation of P in many paddy soils of Java.

Table 4a. The XRF total elemental analysis of the clay fraction of the representative soils.

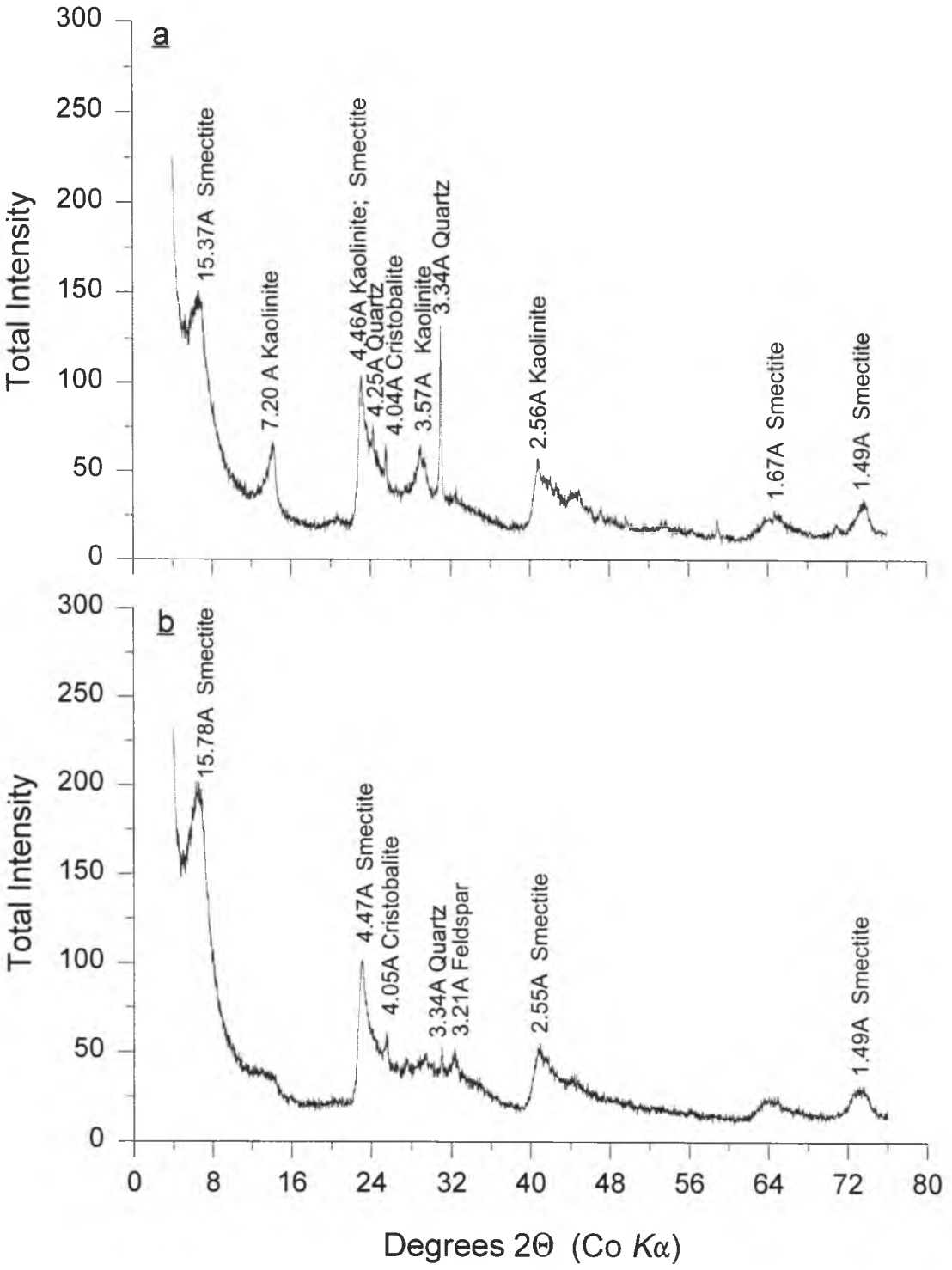
Soils	SiO_2	TiO_2	Al_2O_3	Fe_2O_3
	---------- % ----------			
Serang	48.7	0.761	19.13	7.36
Cianjur	39.6	1.07	24.47	11.56
Kerawang	43.3	0.905	22.79	9.31
Brebes	44.5	0.995	18.67	10.29
Purbalingga	45.2	0.675	20.78	8.16
Purwodadi	44.9	0.620	17.30	6.12
Madiun	39.7	0.956	26.90	10.63
Mojokerto	42.0	0.924	20.98	9.56
Silo	43.0	0.862	20.75	10.26
Jenggawah	46.0	0.952	16.58	9.23

Table 4b. The XRF total elemental analysis of the clay fraction of the representative soils.

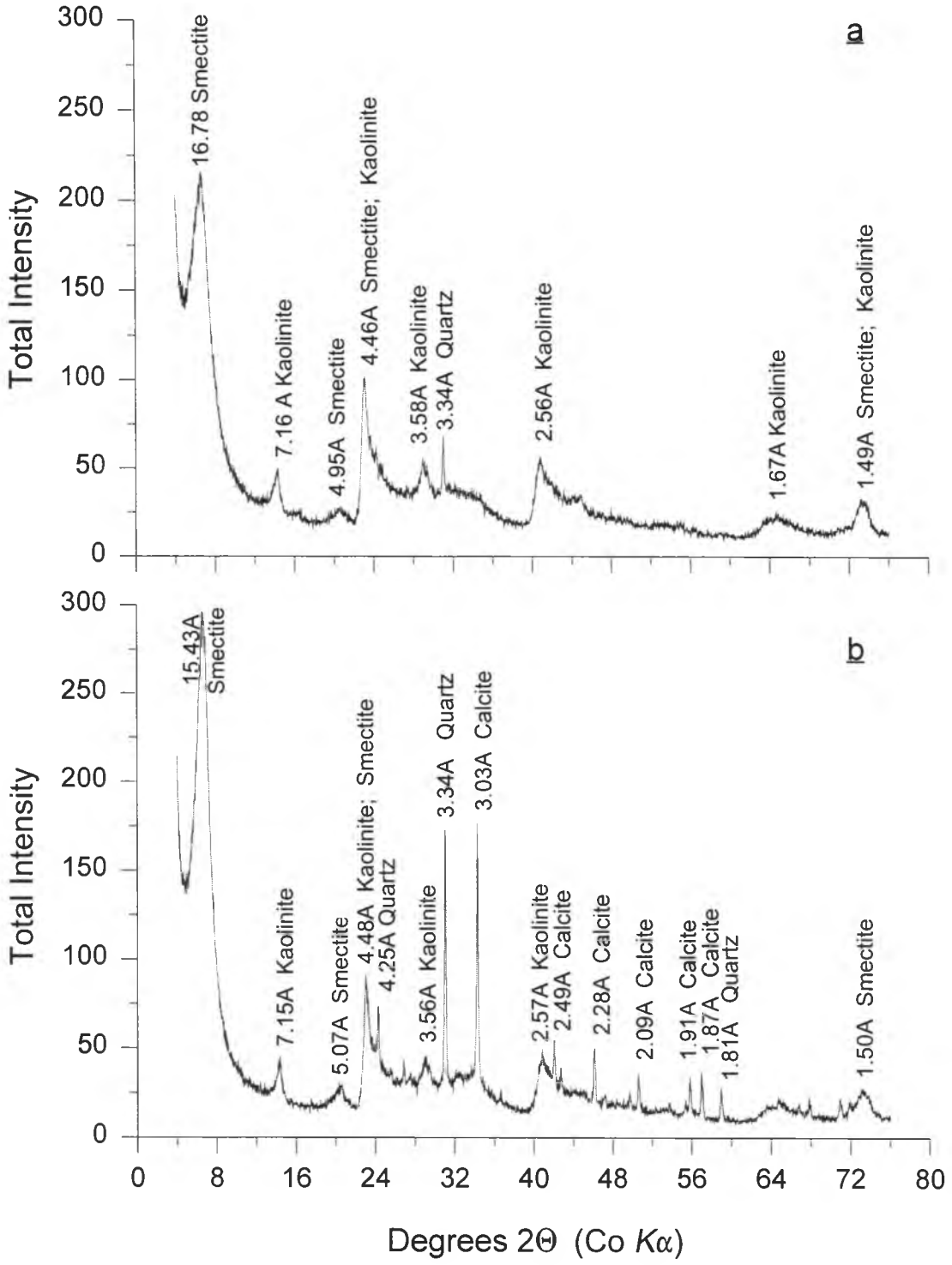
Soils	MgO	CaO	K_2O	P_2O_5
	%			
Serang	0.358	0.649	0.382	0.135
Cianjur	0.704	0.489	0.183	0.215
Kerawang	1.25	0.751	0.634	0.117
Brebes	1.66	1.46	0.448	0.147
Purbalingga	2.21	1.22	1.06	0.096
Purwodadi	1.65	5.90	0.855	0.137
Madiun	0.337	0.570	0.104	0.169
Mojokerto	0.686	1.25	0.216	0.262
Silo	0.752	1.04	0.252	0.169
Jenggawah	1.07	1.63	0.474	0.233



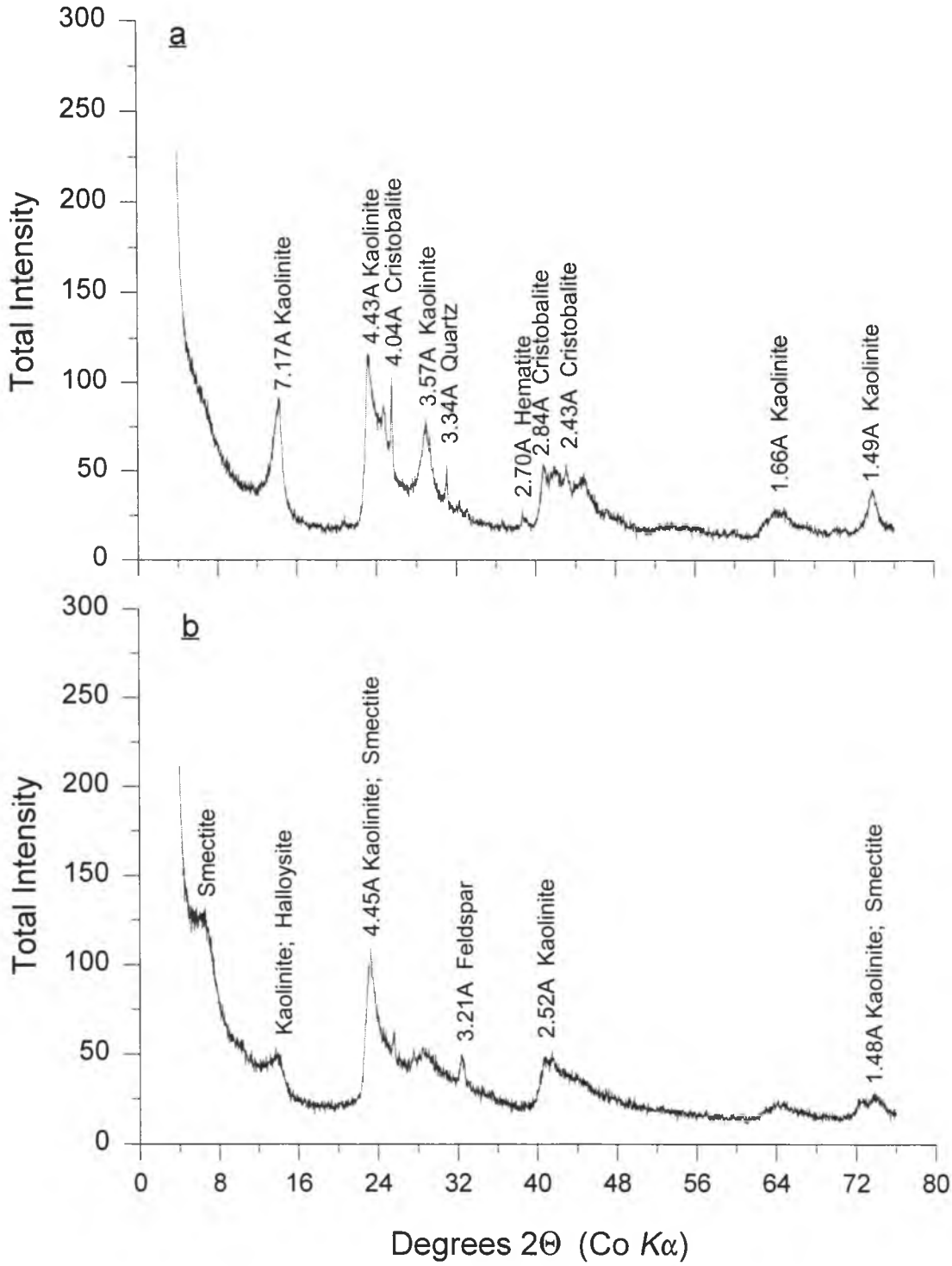
Figures 9a & b. X-ray diffraction patterns for clay fraction of Serang (a) and Cianjur (b) soils.



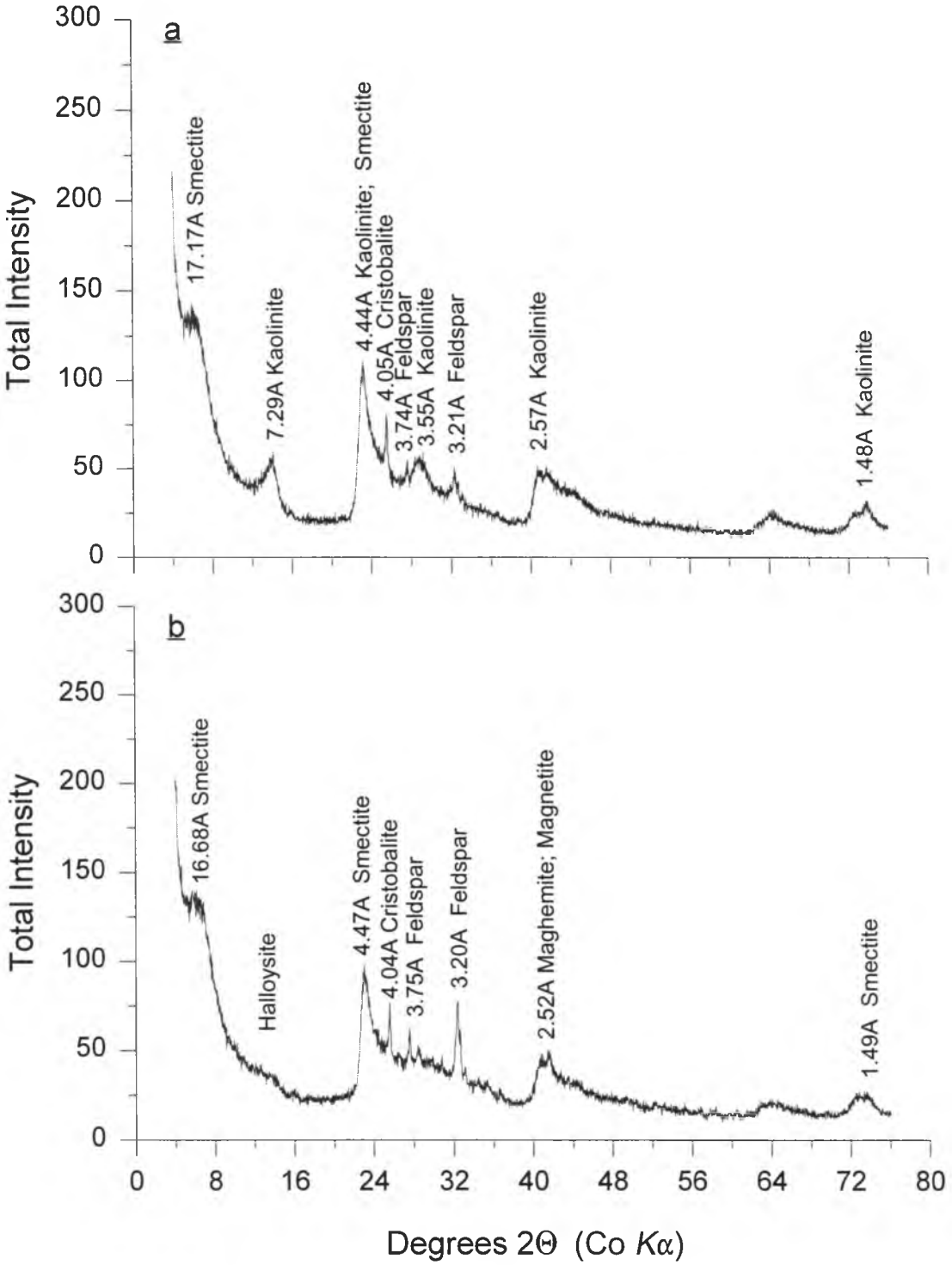
Figures 10a & b. X-ray diffraction patterns for clay fraction of Kerawang (a) and Brebes (b) soils.



Figures 11a & b. X-ray diffraction patterns for clay fraction of Purbalingga (a) and Purwodadi (b) soils.



Figures 12a & b. X-ray diffraction patterns for clay fraction of Madiun (a) and Mojokerto (b) soils.



Figures 13a & b. X-ray diffraction patterns for clay fraction of Silo (a) and Jenggawah (b) soils.

4. 2. Plant Dry Weight and P Content

The purpose of measuring the plant dry weight and plant P content was to analyze the effects of soil types, the amount of P applied, the crop-time, and the interactions among each of them.

The plant dry weight and plant P content were measured at harvest which was at 8 weeks after planting. The analyses of variance of the whole plant dry weight and plant P uptake are shown in Tables 5.

Table 5. Analyses of variance of the plant dry weight (g) and plant P content (g).

		Plant Dry Weight		Plant P content	
Source	DF	F	P>	F	P>
Rep	1	0.25^{ns}	0.6512	0.23^{ns}	0.6628
Time	3	53.78^{**}	0.0042	114.07^{**}	0.0014
Error (a)	3				
Soil	9	75.29^{**}	0.0000	69.18^{**}	0.0000
P	2	4.17^{*}	0.0176	6.41^{**}	0.0024
SoilxTime	27	15.48^{**}	0.0000	20.46^{**}	0.0000
PxTime	6	0.91^{ns}	0.4884	0.51^{ns}	0.8033
SoilxP	18	1.00^{ns}	0.4652	1.09^{ns}	0.3750
SoilxPxTime	54	1.34^{ns}	0.0986	0.86^{ns}	0.7350
Error (b)	116				
Total	239				

^{ns}) non significant; *) significant; **) highly significant.

The effects of the first and second degree interactions between the amount P fertilizer applied with the other two factors were non-significant for all variables. The

effects of soil and time were highly significant for all variables as was the interaction between soil and time.

These results indicated that the amount of P fertilizer applied had no significant effect on the plant dry weight and plant P content of different soil series and in different time (crop). This was true since the amount of extractable P in most of the representative soils exceeded the high category for both methods of extractable P. The only significant interaction was that between soil with time, which indicated that time (crop) had a significant effect on the decrease of plant dry weight and plant P content in all soils. The mean values of the plant dry weight and plant P content of the SoilxTime interaction are shown in Table 6.

The Tukey critical values for interaction mean comparison of both plant dry weight and plant P content are shown in Table 7.

The effect of time (crop) generally indicates a significant decrease on total plant dry weight on the second crop and increase again on the third and fourth crops (Figures 14a & b to 18a & b). While the effect of time (crop) on the total plant P content commonly shows a significant decrease after the first crop, but no significant difference between second, third and fourth crops. (Figures 19a & b to 23a & b).

Table 6. Mean values of the rice plant dry weight and plant P content, of the SoilxTime interaction.

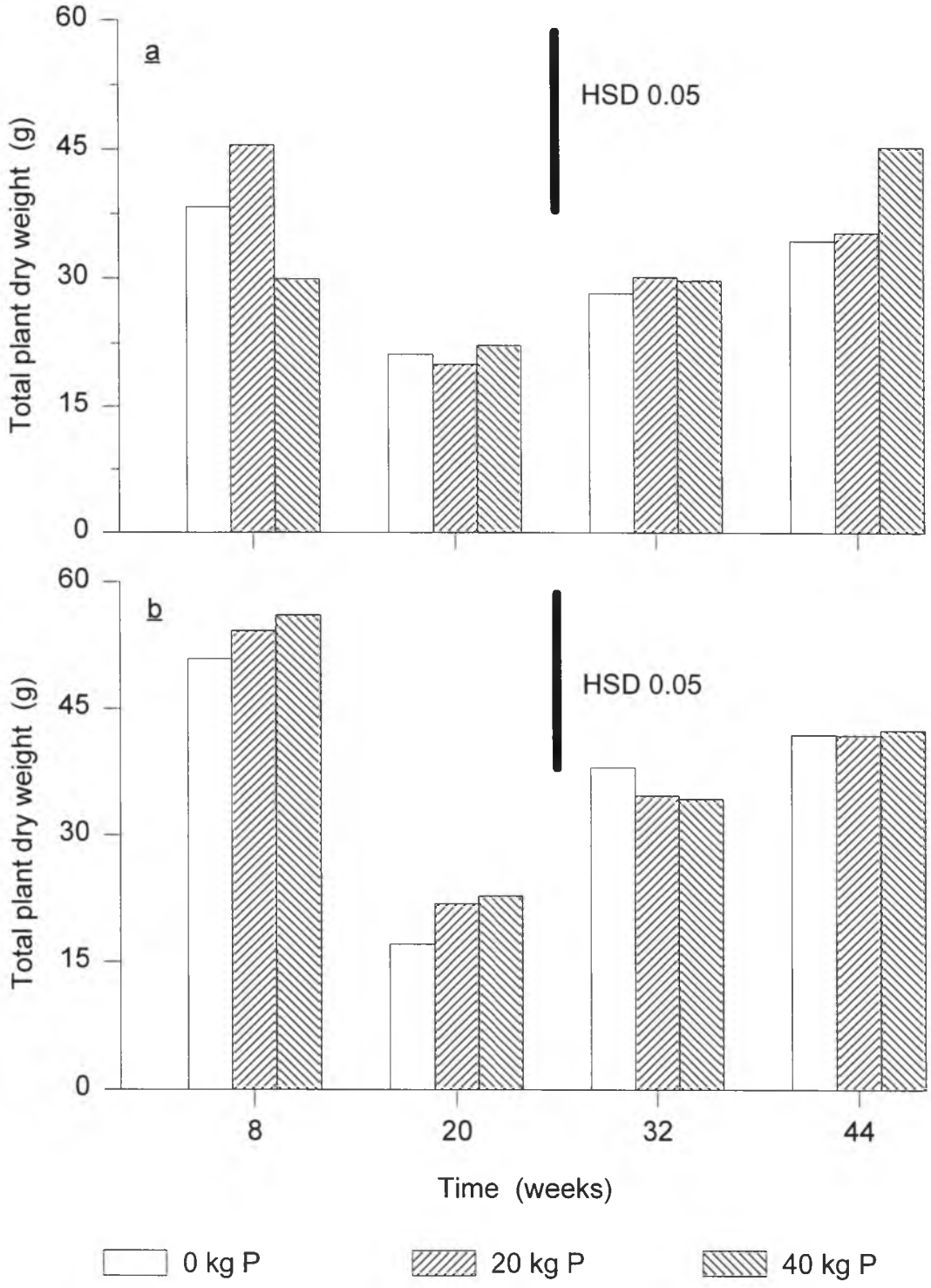
Soil	Time/Crop	Mean Plant Dry Weight (g)	Mean Plant P (g)
BREBES	1	36.7	0.094
BREBES	2	20.6	0.054
BREBES	3	27.6	0.058
BREBES	4	34.9	0.068
CIANJUR	1	53.8	0.183
CIANJUR	2	20.6	0.061
CIANJUR	3	35.7	0.073
CIANJUR	4	42.1	0.081
JENGGAWAH	1	79.2	0.184
JENGGAWAH	2	29.4	0.066
JENGGAWAH	3	41.0	0.068
JENGGAWAH	4	31.4	0.047
KERAWANG	1	40.3	0.087
KERAWANG	2	21.5	0.050
KERAWANG	3	38.4	0.080
KERAWANG	4	40.5	0.088
MADIUN	1	37.6	0.077
MADIUN	2	13.8	0.035
MADIUN	3	24.8	0.051
MADIUN	4	32.3	0.058
MOJOKERTO	1	25.1	0.060
MOJOKERTO	2	15.8	0.037
MOJOKERTO	3	22.0	0.037
MOJOKERTO	4	15.0	0.020
PURBALINGGA	1	35.8	0.094
PURBALINGGA	2	22.7	0.056
PURBALINGGA	3	38.5	0.082
PURBALINGGA	4	39.6	0.080
PURWODADI	1	28.3	0.065
PURWODADI	2	7.1	0.018
PURWODADI	3	8.9	0.023
PURWODADI	4	29.2	0.065
SERANG	1	37.9	0.114
SERANG	2	21.2	0.051
SERANG	3	29.4	0.049
SERANG	4	38.3	0.064
SILO	1	47.5	0.146
SILO	2	18.7	0.055
SILO	3	31.6	0.076
SILO	4	42.1	0.071

Table 7. Critical values for comparison of the (SoilxTime) interaction.

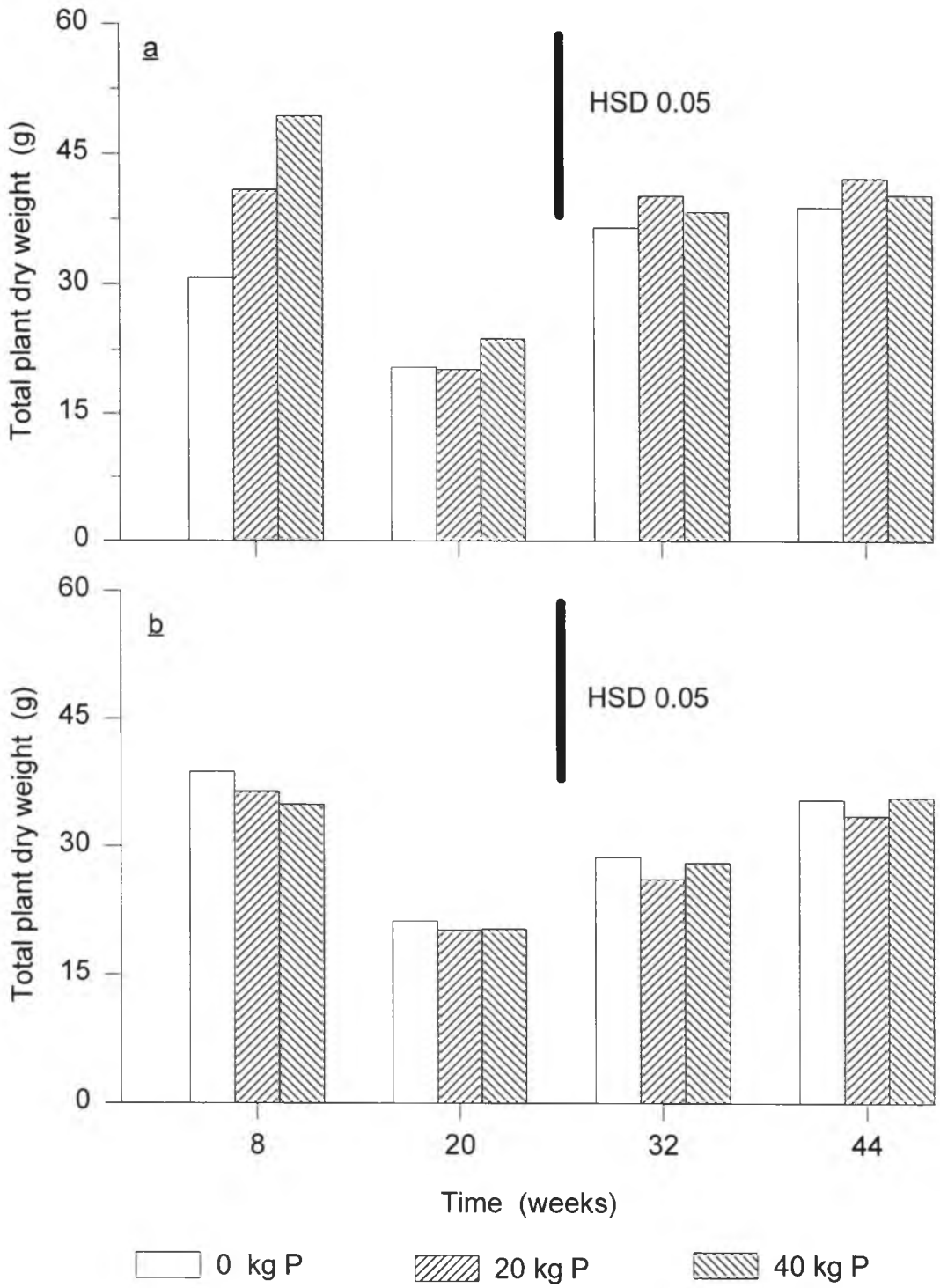
Parameter	Standard Error of the mean difference for comparison†	Weighted 5% HSD (Tukey) Critical value†
Total Plant Dry Weight	3.853330	(Time in each soil) 20.6479
Total Plant P Content	0.009104	(Time in each soil) 0.04644

†) Calculated based on Gomez and Gomez (1984).

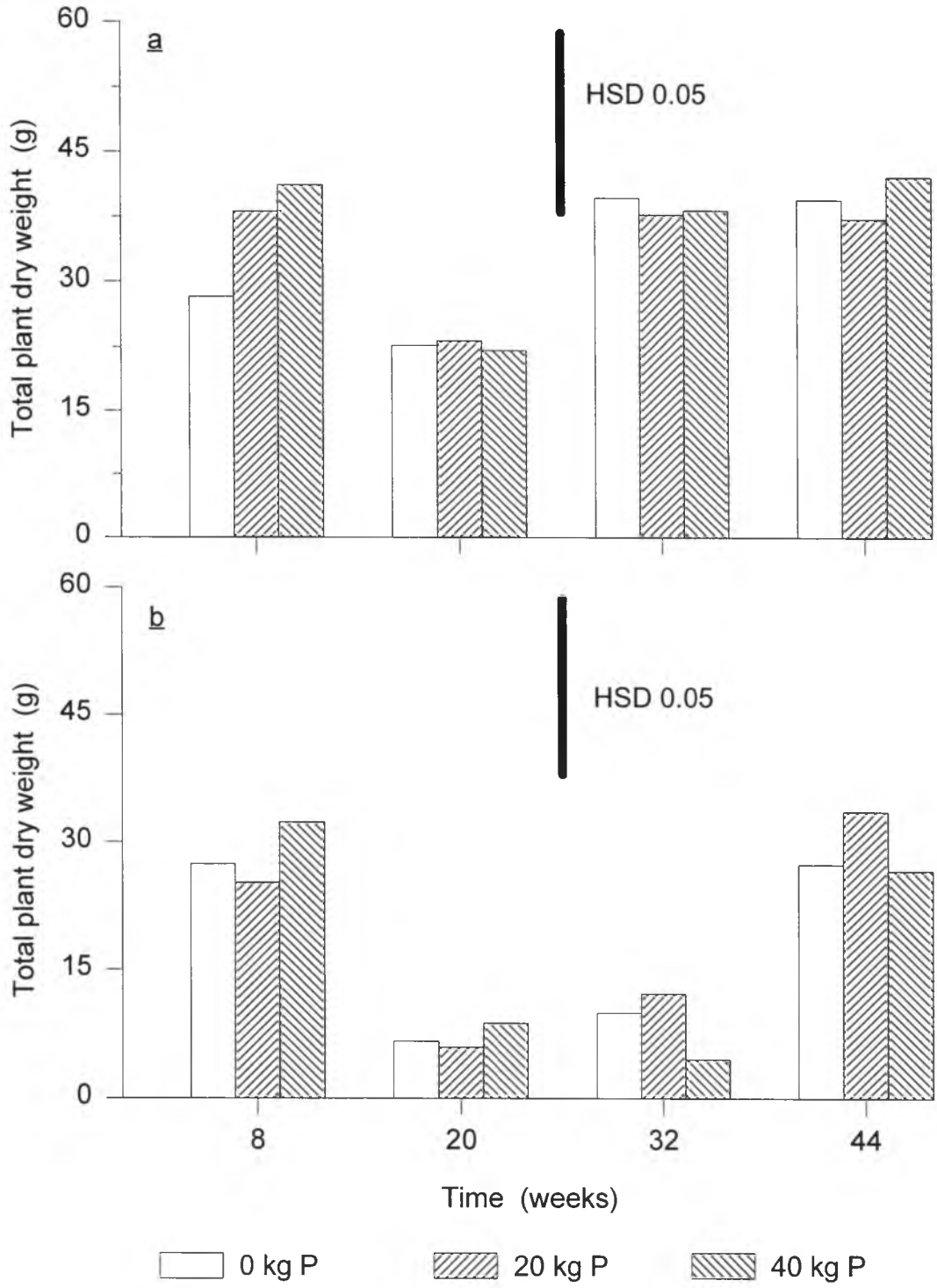
There were differences in plant performance with time (crop) as reflected in total plant dry weight and total plant P content among crops on each soil. These differences most likely were not the effect of soil P deficiency since almost all of the studied soils had extractable P levels that exceeded the critical level of P. Only one soil (Serang soil) had extractable P below the critical level after week 12, which was the beginning of the second crop. There must be some other factors that caused the decline of plant performance after the first crop. One possible reason more likely caused by some external factors such as sunlight intensity, temperature, etc due to change in season. Unfortunately, however, there were no appropriate data to support this speculation.



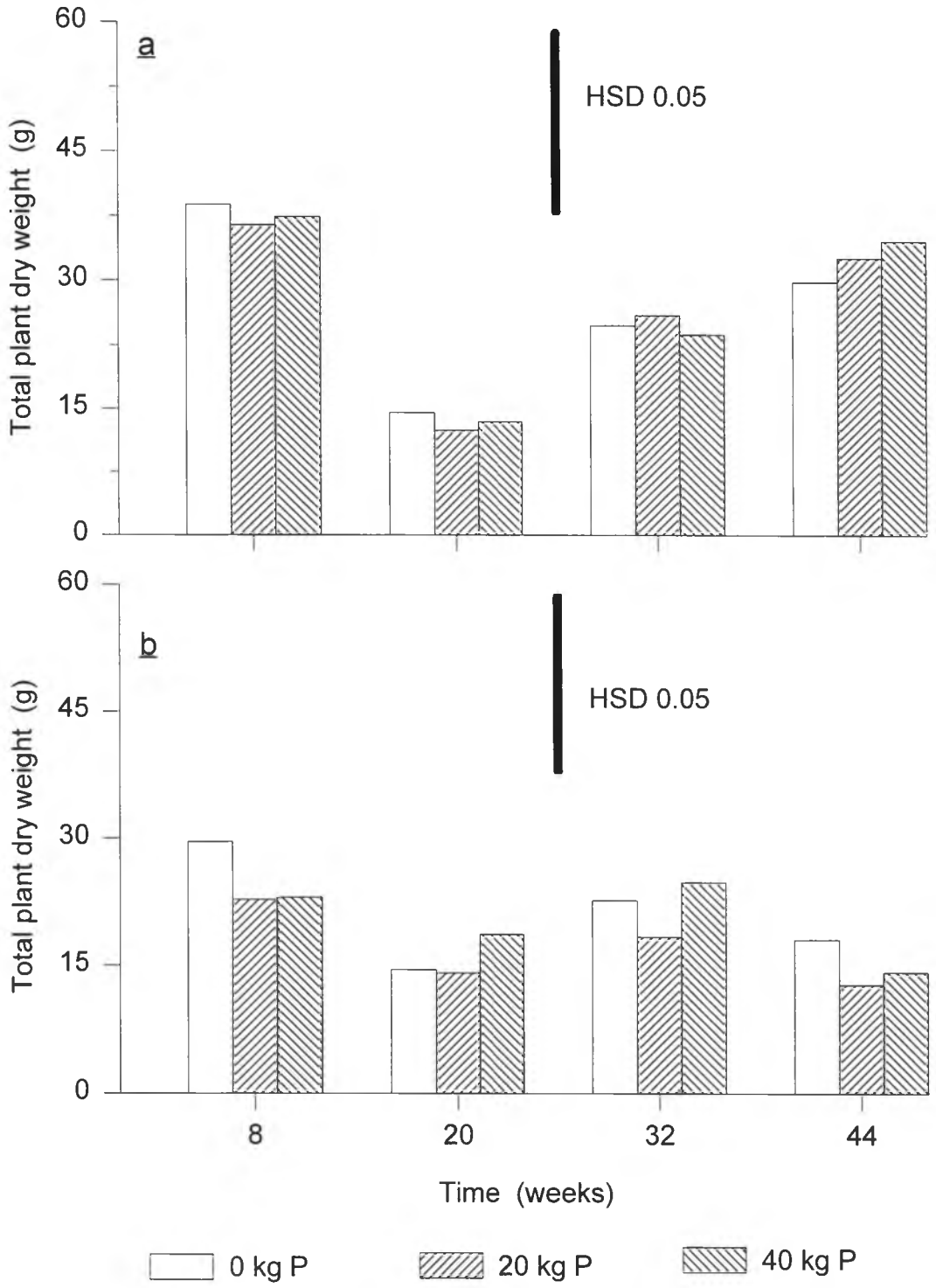
Figures 14a & b. Total plant dry weights of Serang (a) and Cianjur (b) soils.



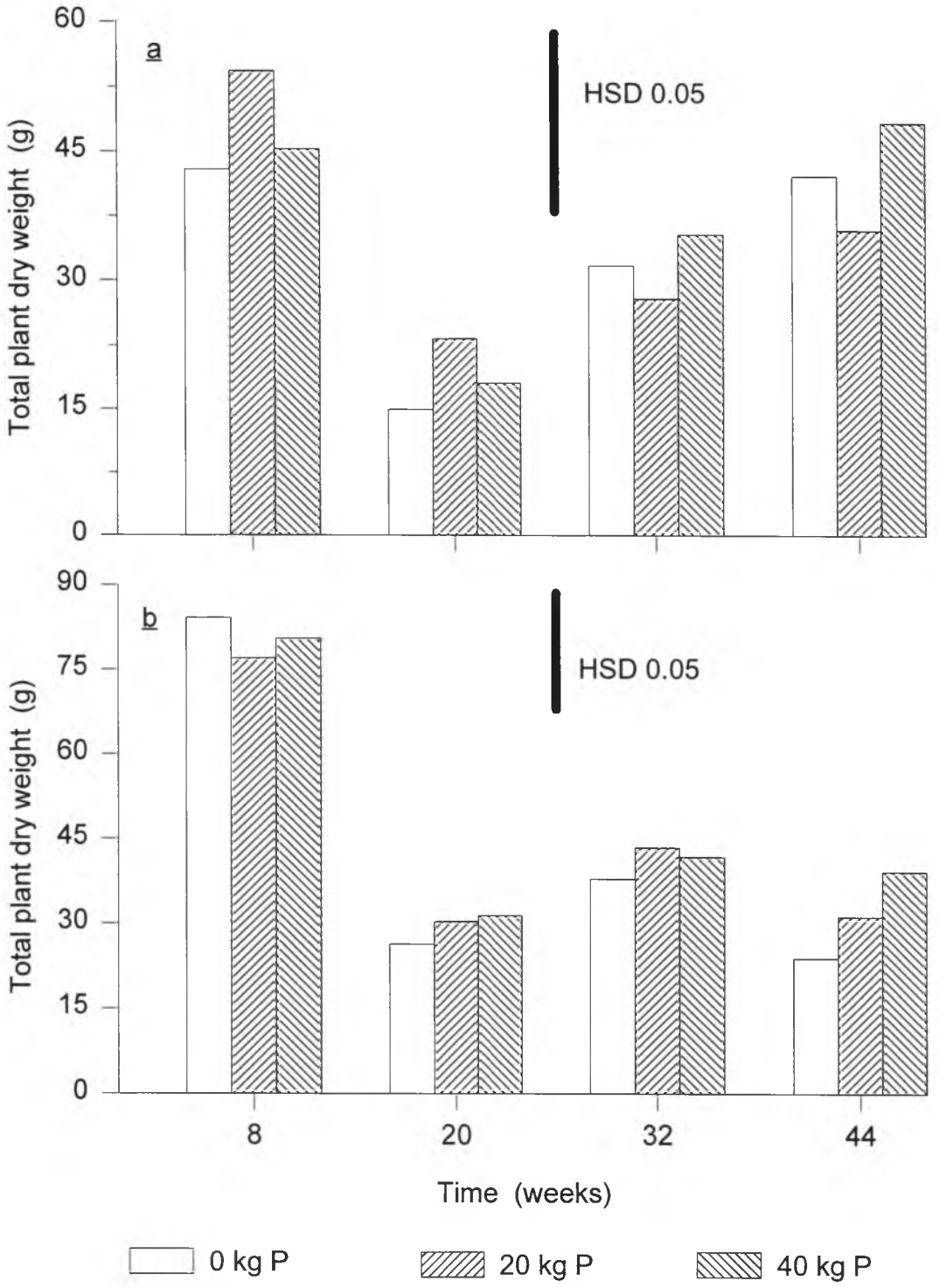
Figures 15a & b. Total plant dry weights of Kerawang (a) and Brebes (b) soils.



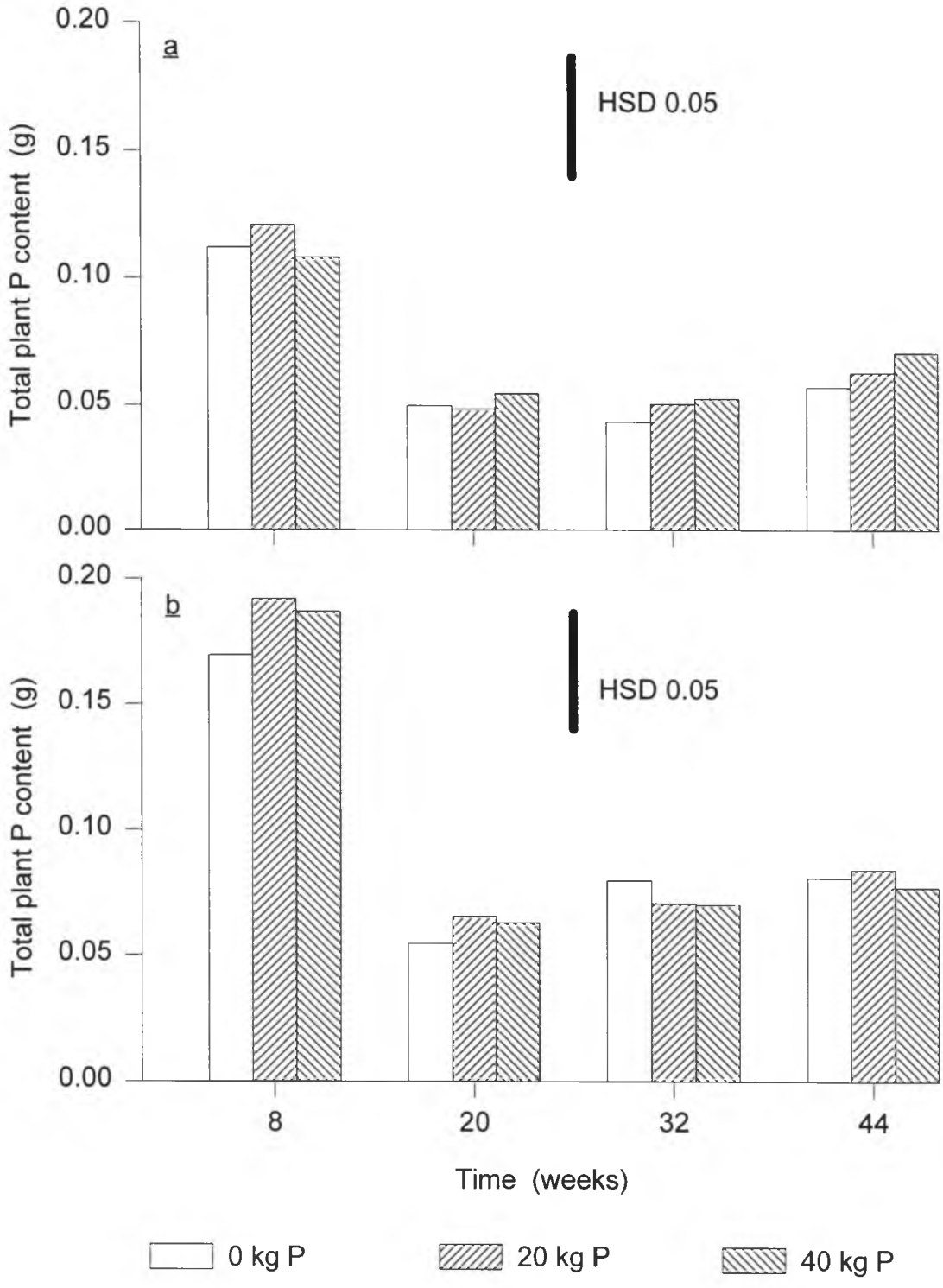
Figures 16a & b. Total plant dry weights of Purbalingga (a) and Purwodadi (b) soils.



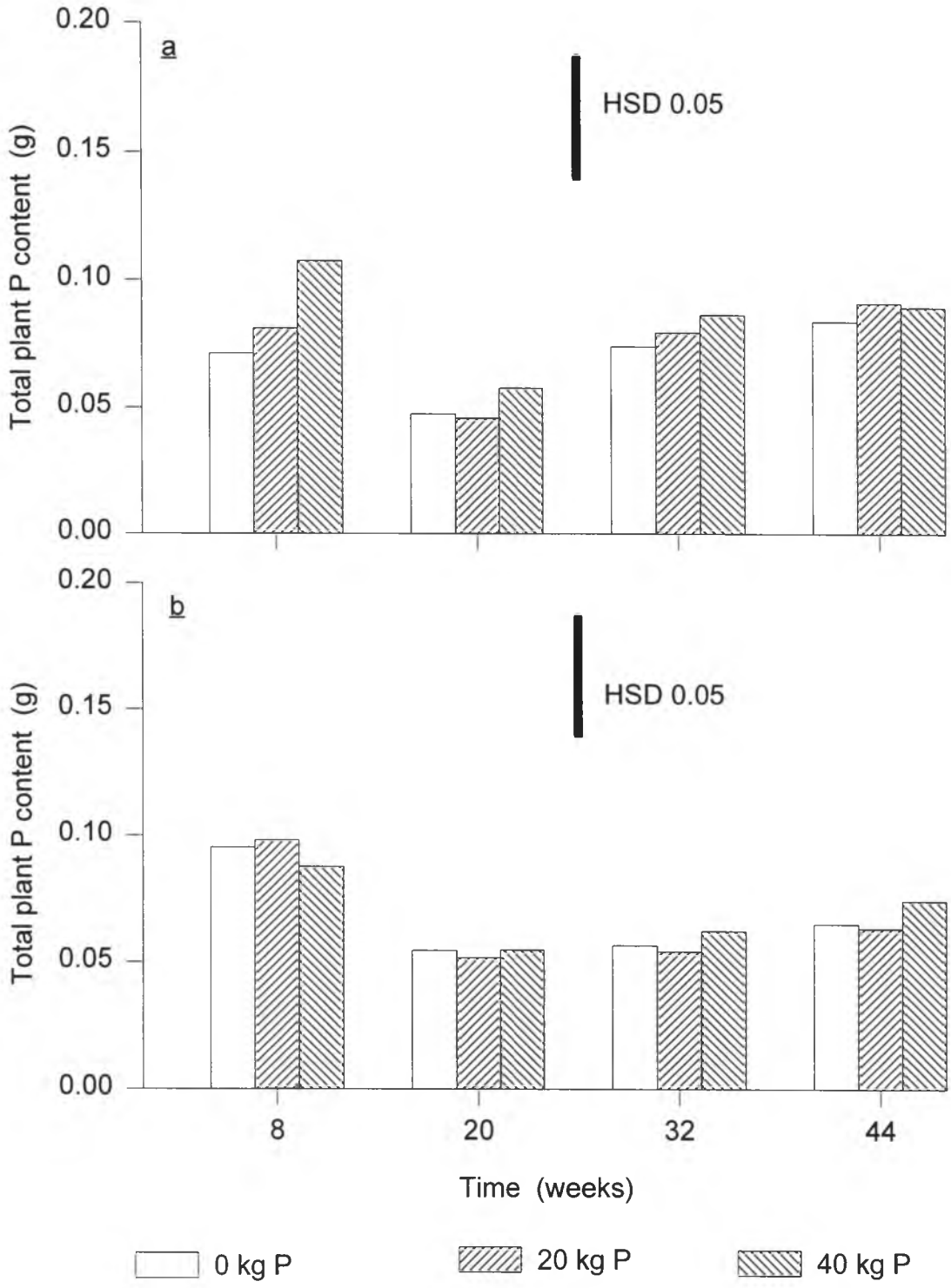
Figures 17a & b. Total plant dry weights of Madiun (a) and Mojokerto (b) soils.



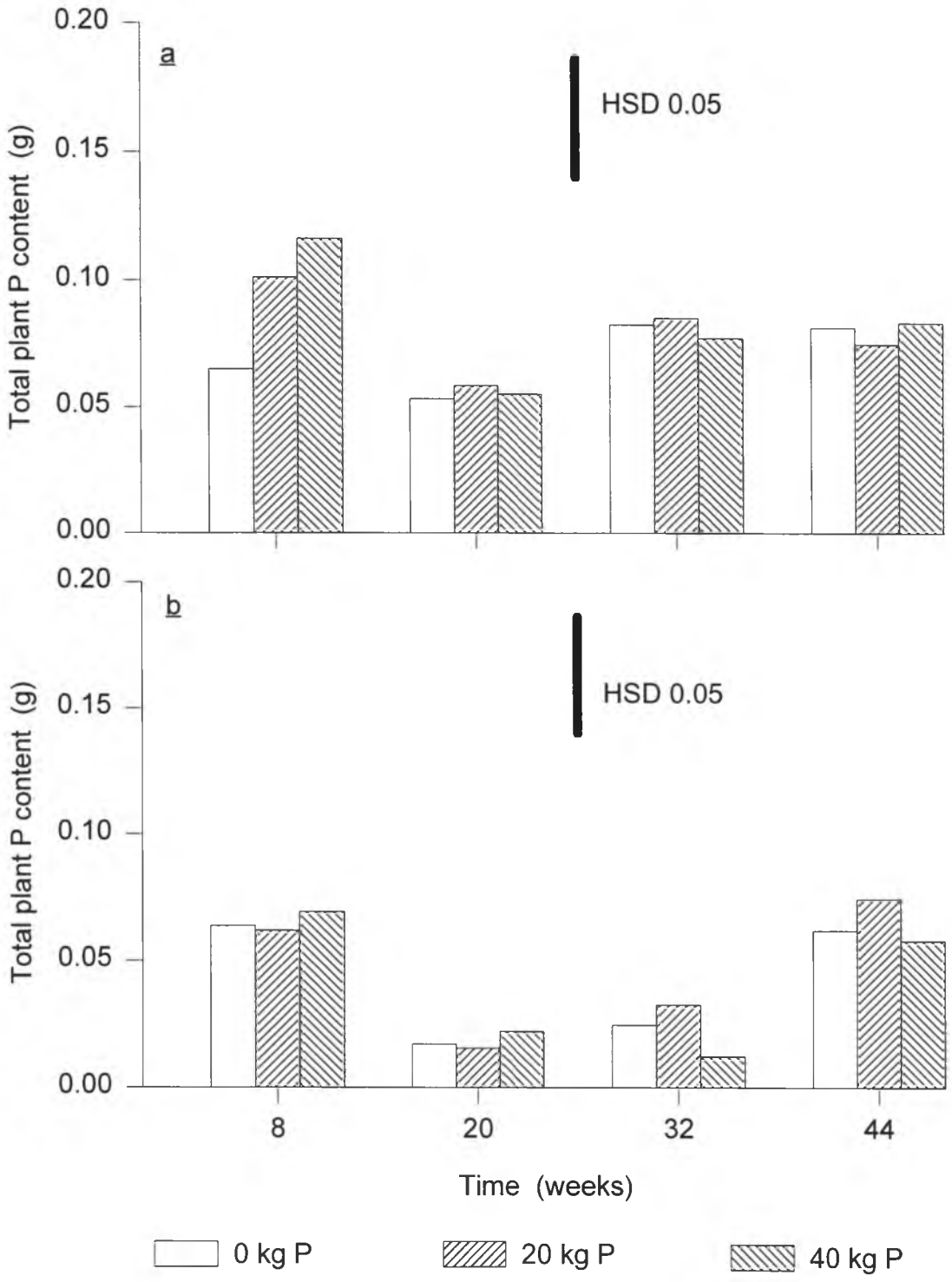
Figures 18a & b. Total plant dry weights of Silo (a) and Jenggawah (b) soils.



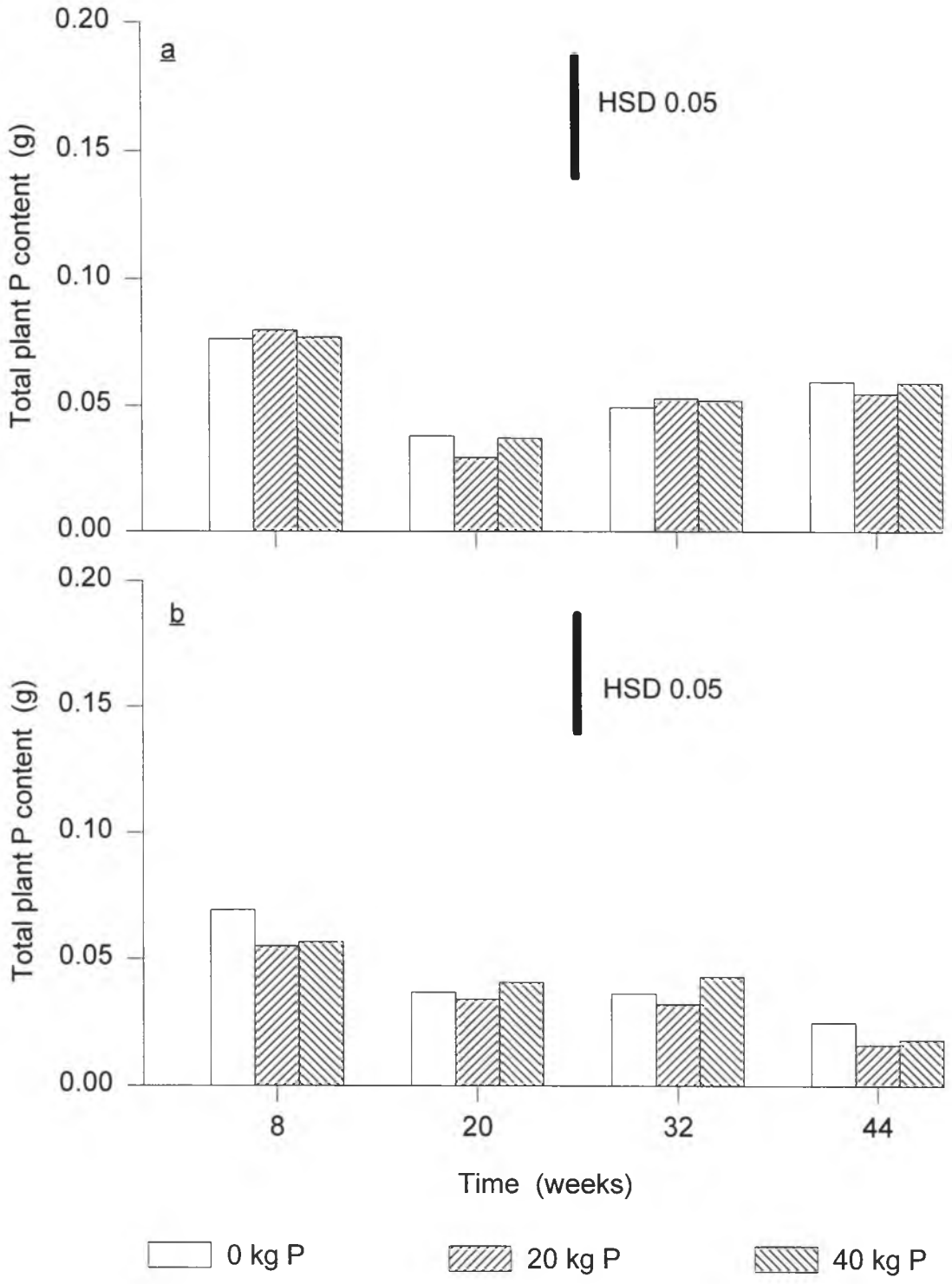
Figures 19a & b. Total plant P content of Serang (a) and Cianjur (b) soils.



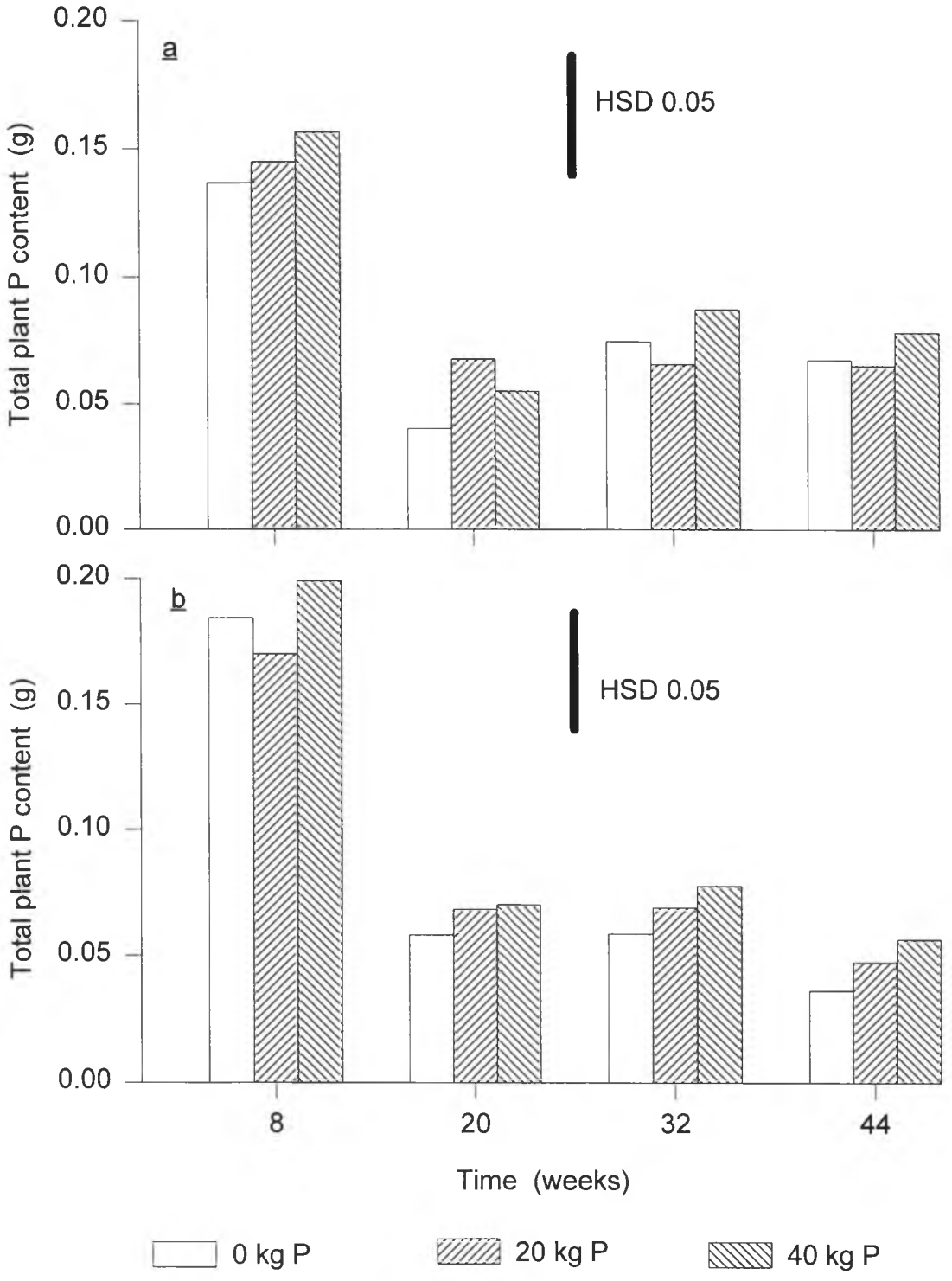
Figures 20a & b. Total plant P content of Kerawang (a) and Brebes (b) soils.



Figures 21a & b. Total plant P content of Purbalingga (a) and Purwodadi (b) soils.



Figures 22a & b. Total plant P content of Madiun (a) and Mojokerto (b) soils.



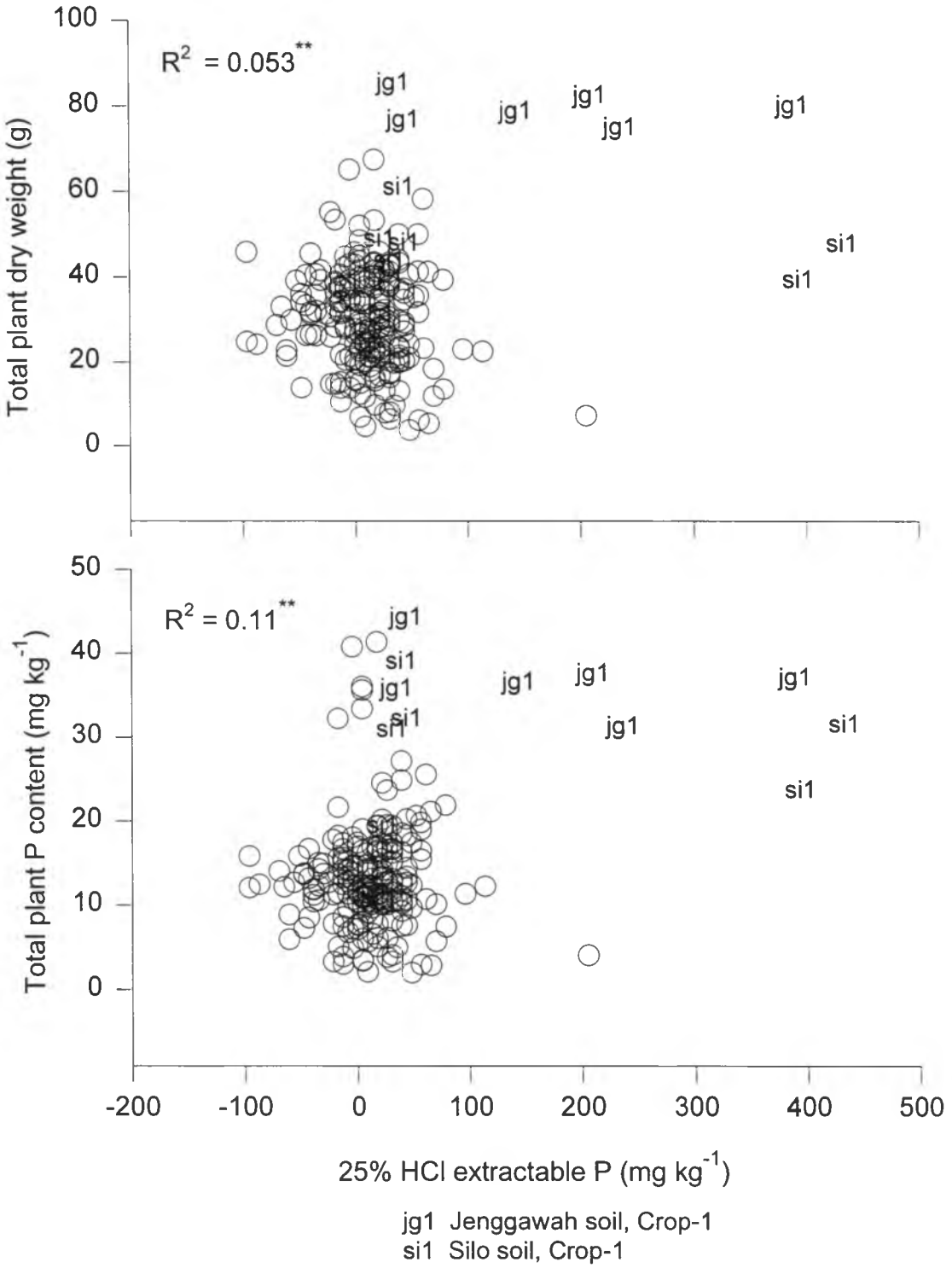
Figures 23a & b. Total plant P content for Silo (a) and Jenggawah (b) soils.

4. 3. Relationship between Soil Extractable P of Different Methods and Plant Response

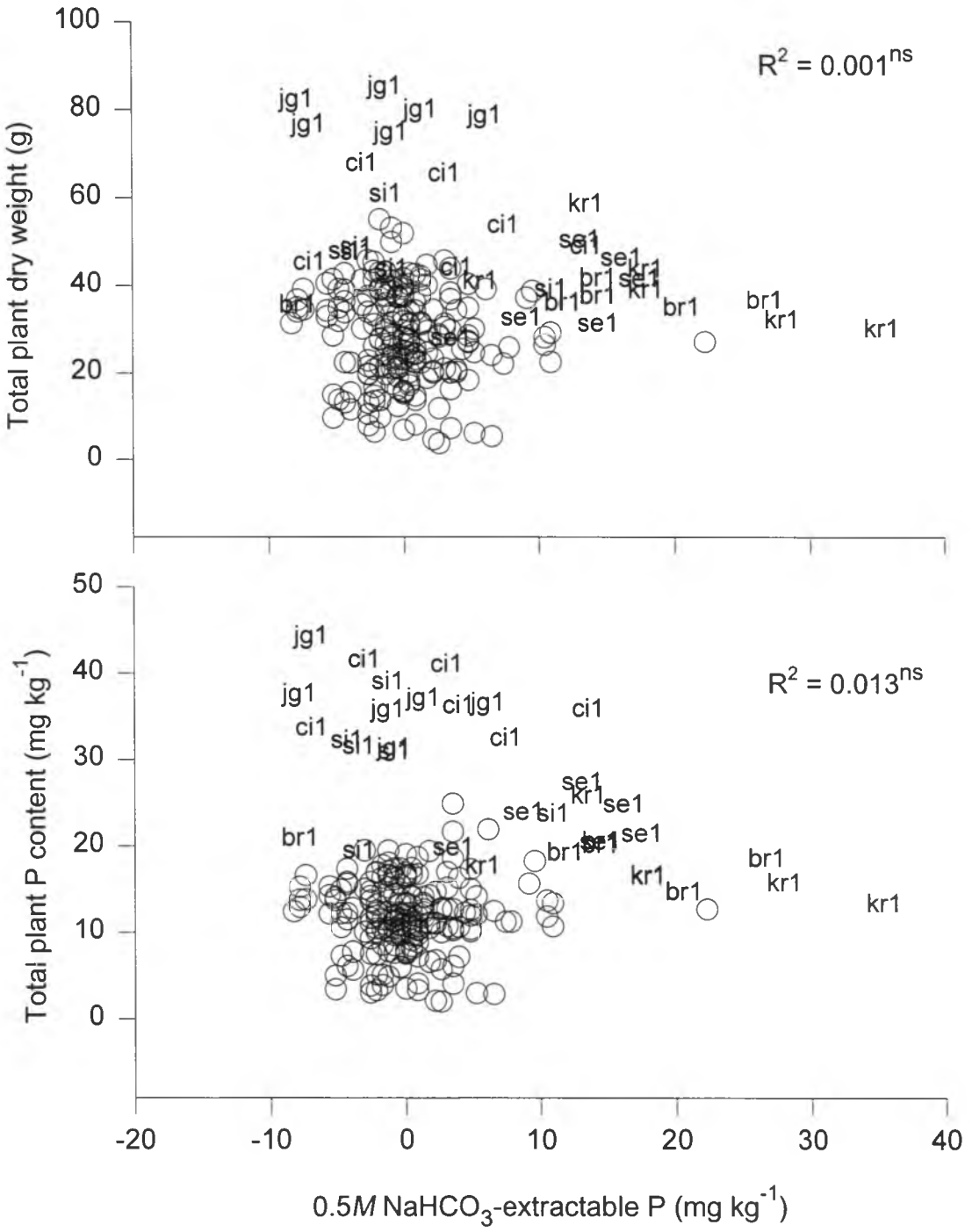
The objective of analyzing the relationship between soil extractable P with the plant responses was to determine which method was more appropriate for measuring extractable P in paddy soils. As specified in the Materials and Methods section, two methods of measuring extractable P in soils, 0.5*M* $NaHCO_3$ pH 8.5 and 25% HCl were used. The relationship between extractable P and plant response was developed by correlating the difference in extractable P at planting and harvest time with the plant responses, such as total plant dry weight and total plant P uptake.

Only the 25% HCl method, however, showed a significant correlation with plant response. The coefficients of determination between 25% HCl-extractable P with total plant dry weight and total plant P content were 0.053^{**} and 0.11^{**} (Figures 24 and 25). While the coefficient of determination between 0.5*M* $NaHCO_3$-extractable P with total plant dry weight and total plant P content were 0.001^{ns} and 0.013^{ns} (Figures 26 and 27).

The significant correlation between 25% HCl-extractable P with the plant responses correspond with results of researchers of the Centre for Soil and Agroclimate Research Sri (Adiningsih and Widjaja-Adhi, 1994). Nursyamsi *et al.* (1994) also found that the 25% HCl P extraction method was superior to the 0.5*M* $NaHCO_3$, Bray 1, and Truog methods for extractable P in correlation with the rice



Figures 24 & 25. Relationship of total plant dry weight and total plant P content with 25% HCl-extractable P.



Figures 26 & 27. Relationship of total plant dry weight and total plant P content with 0.5*M* $NaHCO_3$-extractable P.

filled grain dry weight. Those data are one of the reasons why CSAR has selected 25% HCl as the standard procedure to measure extractable P in paddy soils.

Santoso and Sudjadi (1974) found that the critical level for 25% HCl-extractable P to achieve normal rice growth and yield was 20 mg P_2O_5 $100g^{-1}$ soil, which is equal to 87.3 mg P kg^{-1} soil. The critical level for 0.5*M* $NaHCO_3$-extractable P varied depending on the kind of soils. For grumusol the critical level was 5.3 mg P kg^{-1} soil (Widjaja-Adhi, 1986), but was 4.4 mg P kg^{-1} for other soils (Moersidi *et al.*, 1989; Nursyamsi *et al.*, 1993).

> Note: There are three categories of 25% HCl and 0.5*M* $NaHCO_3$-extractable P classification in paddy soils, low, medium and high. For 25% HCl-extractable P, low if <87.3 mg kg^{-1}, medium if between 87.3- 174.6 mg kg^{-1}, and high if >174.6 mg kg^{-1} (Santoso and Sudjadi, 1974; Moersidi *et al.*, 1989). For 0.5*M* $NaHCO_3$-extractable P, low if <4.4 mg kg^{-1}, medium if between 4.4-10.92 mg kg^{-1}, and high if >10.92 mg kg^{-1} (Moersidi *et al.*, 1989; Nursyamsi *et al.*, 1993).

The possible explanation in relation to why HCl-extractable P was more closely related to rice response than 0.5*M* $Na(HCO_3)$ extractable P might be due to the fact that 25% HCl is relatively a strong extractant (Table 8). On the other hand, flooded condition increases phosphorus availability in soil due to reduction of ferric compounds, increasing solubility of Ca-P in calcareous soils, organic transformations influencing P release, and increasing P diffusion (Sanyal and De Datta, 1991). This indicates that 25%HCl extractant might be able to assess the phosphorus availability under flooded condition better than 0.5*M* $Na(HCO_3)$ extractant.

Table 8. Ratios between 0.5*M* $NaHCO_3$- and 25%HCl-extractable P to total P (by concentrated sulfuric acid+perchloric acid).

Soils	Initial Total P	Initial 25%HCl-P	Initial 0.5*M* $NaHCO_3$-P	Ratio of 25%HCl-P to Total P	Ratio of 0.5*M* $NaHCO_3$-P to Total P
	---------- mg kg^{-1} ----------				
Serang	173	83	11.79	0.48	0.07
Cianjur	701	506	13.54	0.72	0.02
Kerawang	392	170	29.69	0.43	0.08
Brebes	456	240	10.48	0.53	0.02
Purbalingga	370	188	23.58	0.51	0.06
Purwodadi	748	633	11.35	0.85	0.02
Madiun	646	383	22.27	0.59	0.03
Mojokerto	293	127	38.86	0.43	0.13
Silo	743	310	8.73	0.42	0.01
Jenggawah	642	275	20.08	0.43	0.03

4. 4. Predicting Change in Extractable P

Extractable P was measured in every crop at planting and harvest. Extractable P data of both set of pot experiments, with and without rice plants, showed a decline with respect to time (see Figures 28 to 43 and Appendix B to Appendix E: Figures 68 to 91). Generally, the extractable P dropped rapidly from the first to second crop, and then decreased gradually thereafter. This drop in extractable P with time is an important consideration for agricultural practices because it indicates that more extractable P was available shortly after fertilizer application but that extractable P was reduced approaching a constant value with time.

The rapid decrease is also known as the initial fast reaction of extractable P and is usually attributed to a ligand exchange reaction that forms a monodentate bond to Fe or Al (Olsen and Khasawneh, 1980). The slow reaction, on the other hand, has been difficult to characterize and several mechanisms have been suggested. In some soils, however, these decreases were not significant even up to four crops of rice.

Equations [2] and [3] of the chapter Materials and Methods, section 3. 5., were fitted to both 25% HCl and 0.5*M* $NaHCO_3$-extractable P.

The empirical model of equation [2] was used in preference to other models. This model was not used as the final model for predicting the change of the extractable P because it did not include soil properties as variables, and, therefore was not specific to a certain soil. One general mathematical model was sought which includes soil properties as variables, so that it will function as site specific model.

4. 4. 1. Predicting Change in 0.5*M* $NaHCO_3$-extractable P

The results of the linear correlation analyses between 0.5*M* $NaHCO_3$-extractable P with some physical and chemical soil properties showed that soil pH, clay surface area, and calcium carbonate content were significantly positively correlated with 0.5*M* $NaHCO_3$-extractable P for both conditions with and without rice crops. While clay physical activity and initial 0.5*M* $NaHCO_3$-extractable P negatively correlated with 0.5*M* $NaHCO_3$-extractable P (Table 9).

Table 9. Coefficient of correlation of 0.5*M* $NaHCO_3$-extractable P with some soil properties.

Soil Properties	Coefficient of Correlation with 0.5*M* $NaHCO_3$-P	
	Experiment without rice	Experiment with rice
pH	0.445^{**}	0.215^{**}
Clay content	0.013^{ns}	0.182^{**}
15 bar %moisture	-0.084^{ns}	0.007^{ns}
Plasticity Index	-0.079^{ns}	0.052^{ns}
Clay physical activity	-0.110^{*}	-0.316^{**}
Soil surface area	0.087^{ns}	0.057^{ns}
Clay surface area	0.162^{**}	0.101^{*}
Organic carbon	0.132^{**}	0.025^{ns}
Calcium carbonate	0.278^{**}	0.221^{**}
Ammonium Oxalate Fe	-0.253^{**}	0.089^{ns}
Ammonium Oxalate Al	-0.350^{**}	0.014^{ns}
Initial $NaHCO_3$-extractable P	-0.519^{**}	-0.339^{**}

The degrees of freedom = 478; the r(478; 0.01) = 0.118; r(478; 0.05) = 0.090
^{ns}) Non significant; *) significant; and **) highly significant.

The soil properties that mostly correlated to 0.5*M* $NaHCO_3$-extractable P were then selected to solve (or to fit) the site specific equation [3]. More than 180 possible models were tested, but only two best models, having the smallest residual standard errors, were considered.

The coefficients of regression, b1 and b2 as well as the loss constant k, of fitting the empirical model of equation [2] to 0.5*M* $NaHCO_3$-extractable P data of the experiment without and with rice are shown in Tables 10 and 11 respectively. The results of fitting the site-specific model of equation [3] to 0.5*M* $NaHCO_3$-extractable P of both experiments showed that the prediction models included frequently measured soil properties such as initial 0.5*M* $NaHCO_3$-extractable P, organic carbon, soil pH, clay content, and clay physical activity, see Tables 12 and 13.

Table 10. Parameters of fitting equation [2] to 0.5*M* $NaHCO_3$-extractable P of experiment with no rice.

Soil/Location	b0	t-value	b1	t-value	b2	t-value	k	t-value	RSE†
Serang	9.35	12.3	0.038	1.52	11.8	9.18	0.197	3.26	2.85
Cianjur	16.0	12.1	0.017	0.383	0.0002	0.025	-0.210	-0.23	5.04
Kerawang	2.70	2.35	0.040	1.70	6.07	4.61	0.078	1.78	2.68
Brebes	13.8	1.64	0.132	2.29	6.92	0.908	0.037	0.412	6.55
Purbalingga	3.46	1.29	-0.020	-0.616	7.95	3.17	0.053	1.22	3.76
Purwodadi	16.0	8.45	0.143	2.36	7.54	2.45	0.161	0.965	6.83
Madiun	10.8	6.63	0.040	0.873	9.21	3.87	0.118	1.61	5.21
Mojokerto	6.42	7.32	0.094	3.43	2.09	1.49	0.152	0.600	3.11
Silo	14.4	7.09	0.119	1.74	13.3	3.84	0.212	1.29	7.71
Jenggawah	8.55	4.76	0.187	3.35	12.8	4.47	0.148	1.81	6.31

†) Residual Standard Error of the model.

Equations were estimated from 48 observations. The t(44; 0.05) = 2.017; t(44; 0.01) = 2.695.

The model of equation [2] is: $EP_t = b0 + b1\ P + b2\ Exp(-k\ Time)$.

Table 11. Parameters of fitting equation [2] to 0.5*M* $NaHCO_3$-extractable P of experiment with rice.

Soil/Location	b0	t-value	b1	t-value	b2	t-value	k	t-value	RSE†
Serang	1.13	1.24	0.063	2.17	21.1	14.3	0.154	5.72	3.27
Cianjur	11.6	11.3	0.023	0.693	9.03	5.44	0.160	2.15	3.68
Kerawang	4.28	5.34	-0.063	-2.29	23.1	16.5	0.274	4.21	3.14
Brebes	7.97	9.19	-0.058	-1.48	21.8	10.9	0.140	4.46	4.44
Purbalingga	4.27	6.82	-0.018	-0.857	10.6	9.76	0.252	2.77	2.43
Purwodadi	9.07	5.52	0.037	1.21	12.9	7.28	0.071	2.77	3.45
Madiun	11.5	9.36	-0.020	-0.523	10.6	5.49	0.145	2.24	4.28
Mojokerto	3.83	5.24	0.014	0.657	7.36	6.57	0.132	2.71	2.47
Silo	11.2	8.93	0.031	0.877	8.51	4.69	0.115	1.94	3.96
Jenggawah	2.89	2.04	0.015	0.601	6.75	4.53	0.068	1.72	2.83

†) Residual Standard Error of the model.

Equations were estimated from 48 observations. The t(44; 0.05) = 2.017; t(44; 0,01) = 2.695.

The model of equation [2] is: $EP_t = b0 + b1\ P + b2\ Exp(-k\ Time)$.

4. 4. 1. 1. Experiment with no Rice

There were two models (model 1a and 2a) selected from hundreds of models resulting from the nonlinear regression analysis (Table 12). Both models incorporated four frequently measured soil properties as model variables - initial 0.5*M* $NaHCO_3$-P (EP_i), soil pH (pH), soil organic carbon (OC), and clay physical activity (CAT). This implied that for routine application both models might have equal cost. Model 1a, however, had residual standard error (RSE) of 0.02 smaller than RSE for model 2a, therefore model 1a was selected as the best model to predict the change in 0.5*M* $NaHCO_3$-extractable P in soil without the influence of crop uptake (in this case rice uptake).

The graphical presentations of both the empirical model of equation [2] and the soil specific model of equation [3] showed that in general predicted extractable P declined rapidly during the first crop up to the beginning of the second crop, then declined asymptotically approaching a constant value, see Figures 28 to 31 and Figures 68 to 73 in the Appendix B.

Table 12. Results on fitting of equation [3] to 0.5*M* $NaHCO_3$-extractable P, experiment with no rice.

Model 1a‡	Parameters (Soil Variables)							
	a EP_i	P_{eq}	b pH	c pH P	d OC $e^{\{.....\}}$	k0	k1 CAT	RSE†
Coefficient:	-0.3349	0.0000	2.8685	0.0150	4.2626	-0.2338	0.5063	5.5885
t-value:	-13.494**	0.0000	23.312**	5.5006**	10.017**	-2.2211*	2.8755**	
Equation:	$EP_t = (-0.3349\ EP_i - 0.0) + (2.8685\ pH) + (0.0150\ pH\ P) + \{4.2626\ OC\ e^{\{-(-0.2338+0.5063\ CAT)\ Time\}}\}$							
Model 2a	a EP_i	P_{eq}	b pH	c CAT P	d OC $e^{\{.....\}}$	k0	k1 CAT	RSE†
Coefficient:	-0.3436	0.0000	2.9076	0.1155	4.2444	-0.2677	0.5572	5.6051
t-value:	-13.752**	0.0000	24.184*	5.2394**	9.9948**	-2.7186**	2.9759**	
Equation:	$EP_t = (-0.3436\ EP_i - 0.0) + (29076\ pH) + (0.1555\ CAT\ P) + \{4.2444\ OC\ e^{\{-(-0.2677+0.5572\ CAT)\ Time\}}\}$							

Equations were estimated from 480 observations. The t(473; 0.05) = 1.960; t(473; 0.01) = 2.576.

†) Residual Standard Error of the model.

‡) Selected as the prediction model and for the final plot.

ns) = non significant; *) = significant; **) = highly significant.

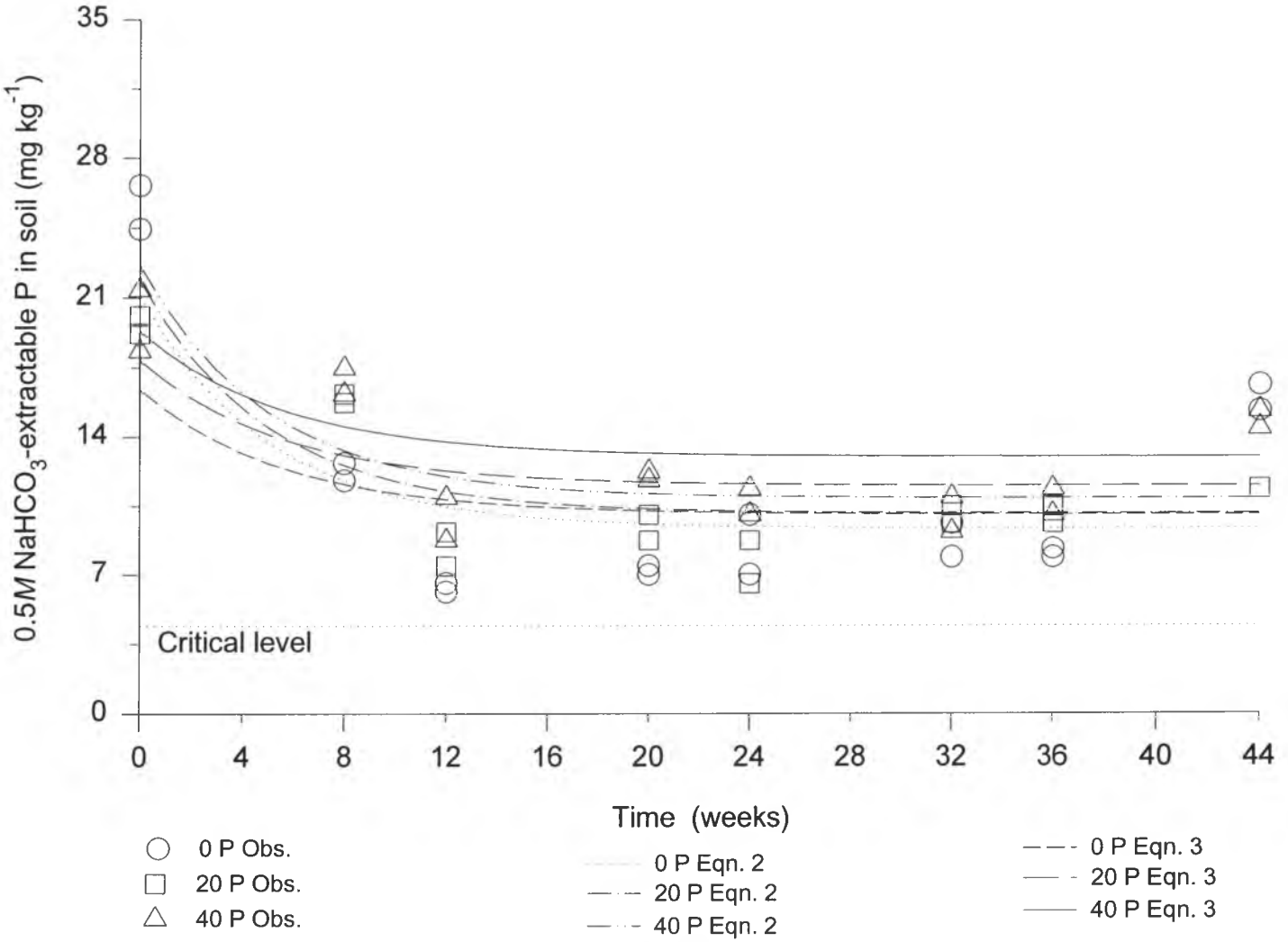


Figure 28. Observed and predicted 0.5*M* $NaHCO_3$-extractable P of Serang soil without rice crops.

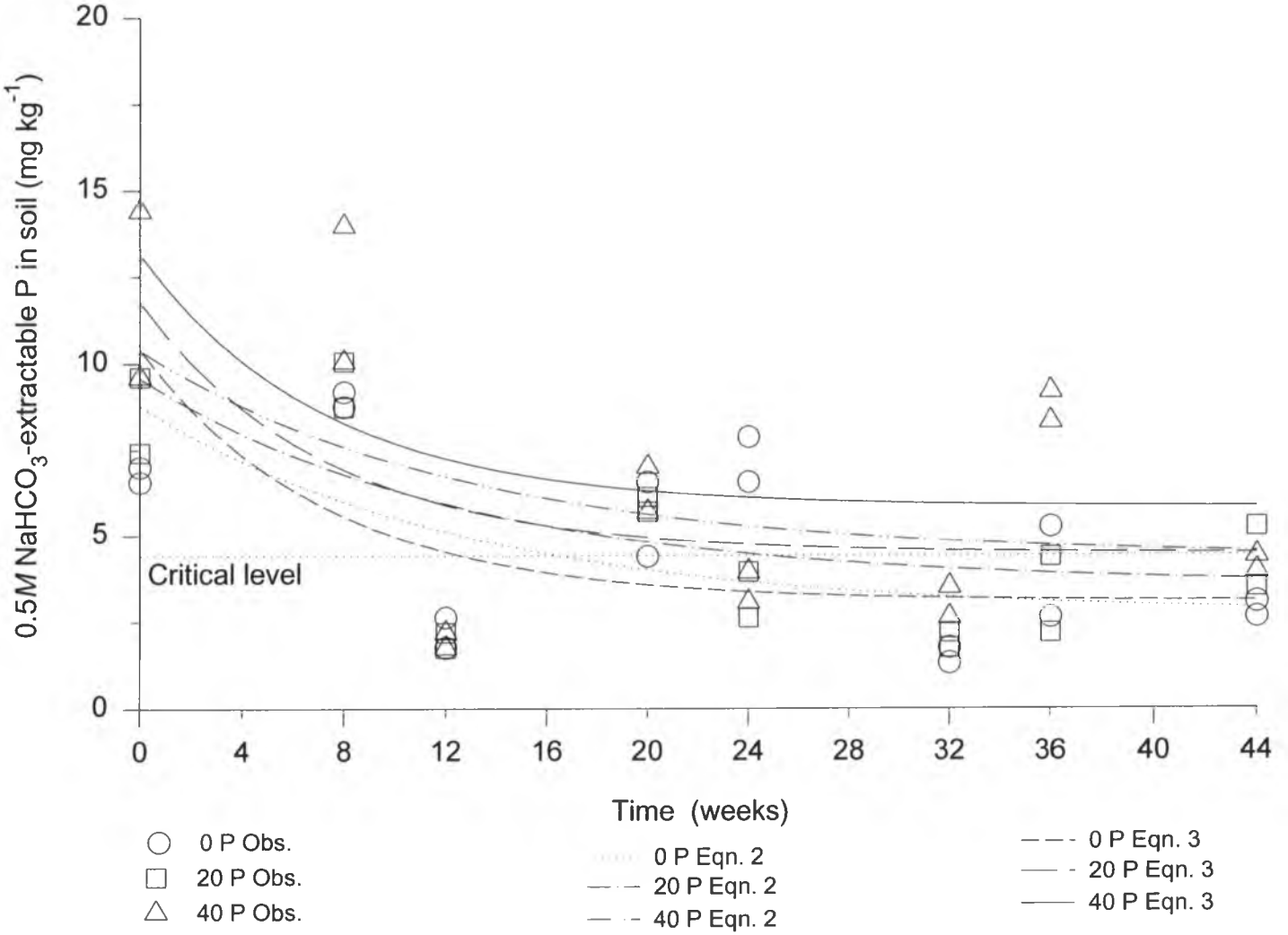


Figure 29. Observed and predicted 0.5*M* $NaHCO_3$-extractable P of Kerawang soil without rice crops.

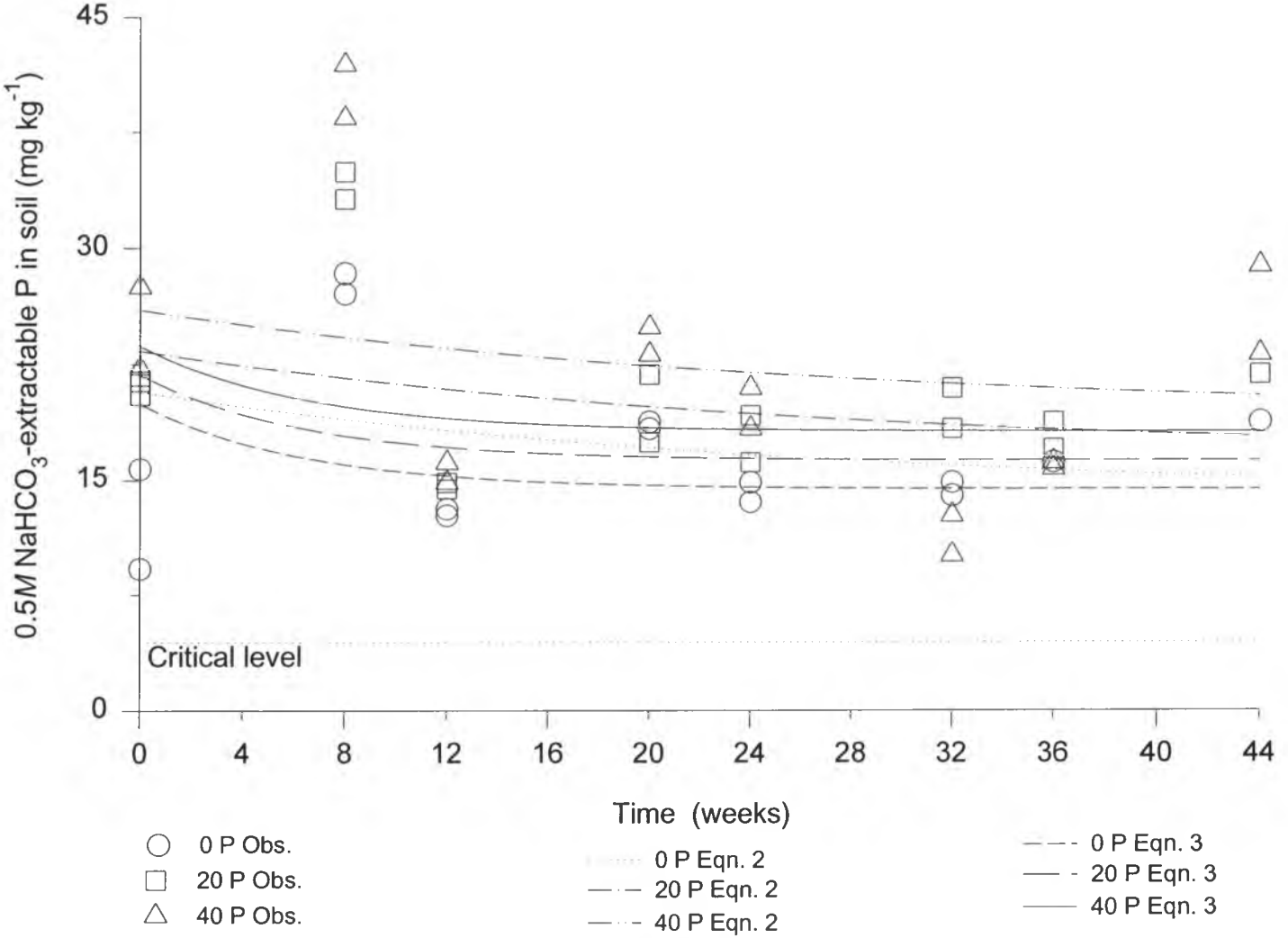


Figure 30. Observed and predicted 0.5*M* $NaHCO_3$-extractable P of Brebes soil without rice crops.

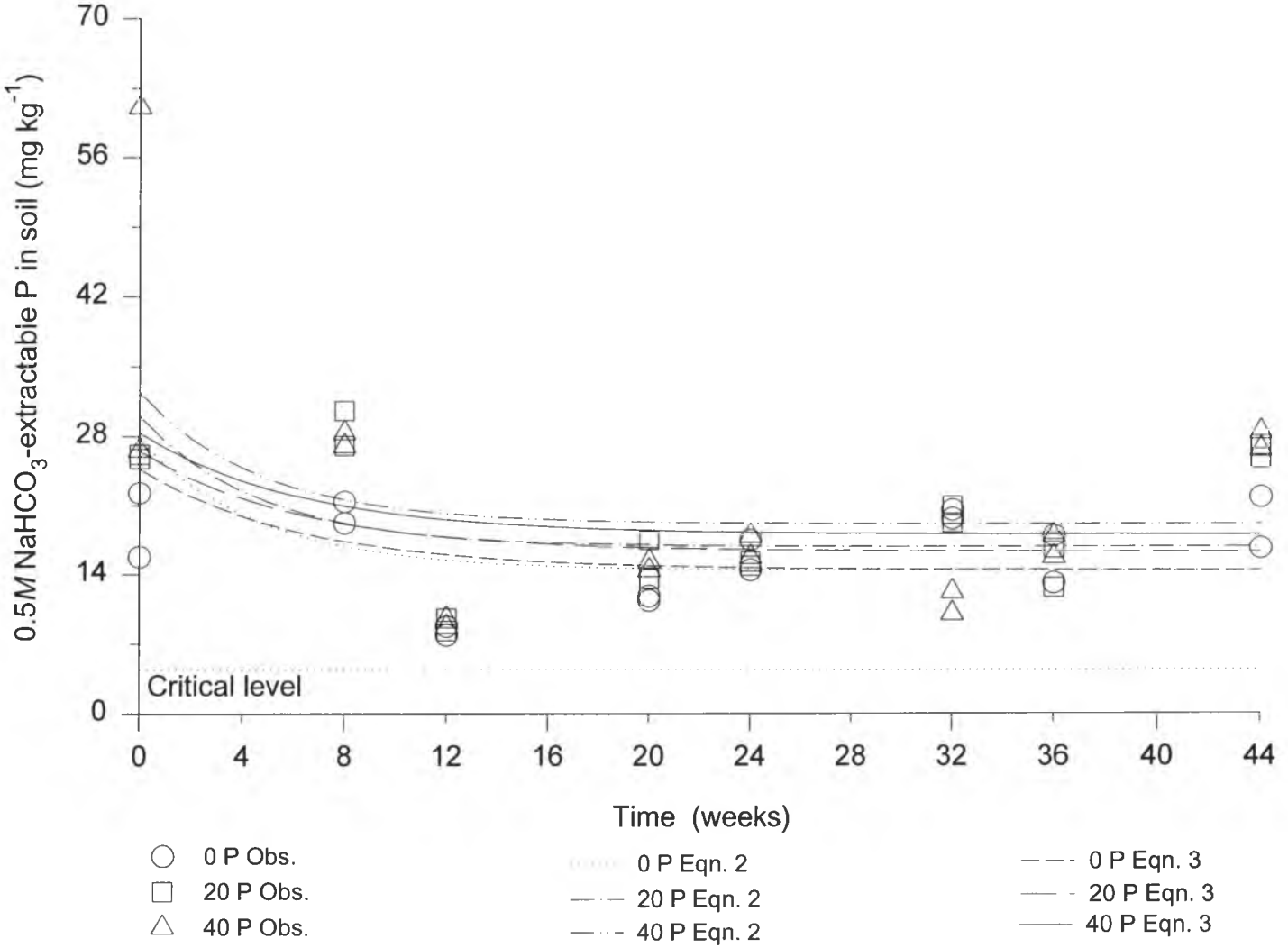


Figure 31. Observed and predicted 0.5*M* $NaHCO_3$-extractable P of Silo soil without rice crops.

Model 1a revealed that soil pH contributed an important role on the linear part of the nonlinear regression model, while soil organic carbon and clay physical activity performed an important role on the nonlinear part. In model 2a clay physical activity also played an important role in the linear portion of the equation. The role of clay physical activity on the nonlinear part of both models indicated that the higher the clay physical activity of the soil the more rapid the decrease in extractable P especially for early crops during the nonlinear portion of the model. These results agreed with the result of the linear correlation between clay physical activity with 0.5*M* $NaHCO_3$-extractable P which was negatively correlated, with a correlation coefficient r = −0.110 which was significant at 5% level of significance.

Uehara and Gillman (1981) described that soils with lower clay physical activity will sorb more P than soils with higher clay physical activity. Kaolinitic clays normally have clay physical activity values less than 0.5, while smectitic clays have greater than 1.0. This suggests that soils with lower clay physical activity would have higher 25% HCl-extractable P.

The soil pH and soil organic carbon positively influenced 0.5*M* $NaHCO_3$-extractable P. Both models showed that the higher the values of soil pH and soil organic carbon the higher the 0.5*M* $NaHCO_3$-extractable P. The coefficients of linear correlation between soil pH and soil organic carbon with 0.5*M* $NaHCO_3$-extractable P were 0.445 and 0.132, respectively, and both were highly significant at the 1 % level of significance.

4. 4. 1. 2. Experiment with Rice

The two best models (model 1b and 2b) were selected from hundreds of models resulting from the nonlinear regression analysis (Table 13). The model 1b had smaller residual standard error by 0.04 compared to that of model 2b. Model 1b has two components with coefficients that were not significant. Those two components were the (CLAY P) interaction and the (k1, CAT). These two components, however, were necessary for the model because, the (CLAY P) component indicates the effect of the amount of P fertilizer applied, and the (k1 CAT) component indicates the effect of clay physical activity that affected the nonlinear decline, fast reaction, of extractable P. Therefore, model 1b was selected as the best model to predict the change of 0.5*M* $NaHCO_3$-extractable P on soils with the influence of rice crops for these two reasons. Model 1b had a smaller residual standard error, and it had fewer soil variables in the equation.

The model 1b consisted of four frequently measured soil variables, initial 0.5*M* $NaHCO_3$-extractable P (EP_i), clay content (CLAY), soil acidity (pH), and clay physical activity (CAT). The graphical presentations of the empirical model of equation [2] and the soil specific model of equation [3] showed that in general predicted extractable P declined rapidly during the first two crops, then declined asymptotically approaching a constant value, see Figures 32 to 35, and Figures 74 to 79 in the Appendix C.

Table 13. Results of fitting equation [3] to 0.5*M* $NaHCO_3$-extractable P, experiment with rice.

	Parameters (Soil Variables)							
Model 1b‡	a EP_i	P_{eq}	b CAT	c CLAY P	d pH $e^{\{.....\}}$	k0	k1 CAT	RSE†
Coefficient:	-0.2504	-26.548	-21.255	-0.0002	2.2079	0.1257	0.0203	4.4994
t-value:	-11.184^{**}	-12.873^{**}	-7.6580^{**}	-1.0790^{ns}	19.528^{**}	1.9651^{*}	0.1286^{ns}	
Equation :	$EP_t = \{-0.2504\ EP_i-(-26.548)\} + (-21.255\ CAT)+(-0.0002\ CLAY\ P) + \{2.2079\ pH\ e^{\{-(0.1257+0.0203\ CAT)\ Time\}}\}$							
Model 2b	a EP_i	P_{eq}	b FE	c CLAY P	d pH $e^{\{.....\}}$	k0	k1 CAT	RSE†
Coefficient:	-0.2252	-7.8663	72.696	-0.0003	2.3578	-0.2076	0.4588	4.5355
t-value:	-9.6122^{**}	-10.919^{**}	4.7873^{**}	-1.1913^{ns}	20.952^{**}	-4.5991^{**}	5.3902^{**}	
Equation:	$EP_t = \{-0.2252\ EP_i-(-7.8663)\} + (72.696\ FE)+(-0.0003\ \ CLAY\ \ P) + \{2.3578\ pH\ e^{\{-(-0.2076+0.4588\ CAT)\ Time\}}\}$							

Equations were estimated from 480 observations. The t(473; 0.05) = 1.960; t(473; 0.01) = 2.576.

†) Residual Standard Error of the model.

‡) Selected as the prediction model and for the final plot.

ns) = non significant; *) = significant; **) = highly significant.

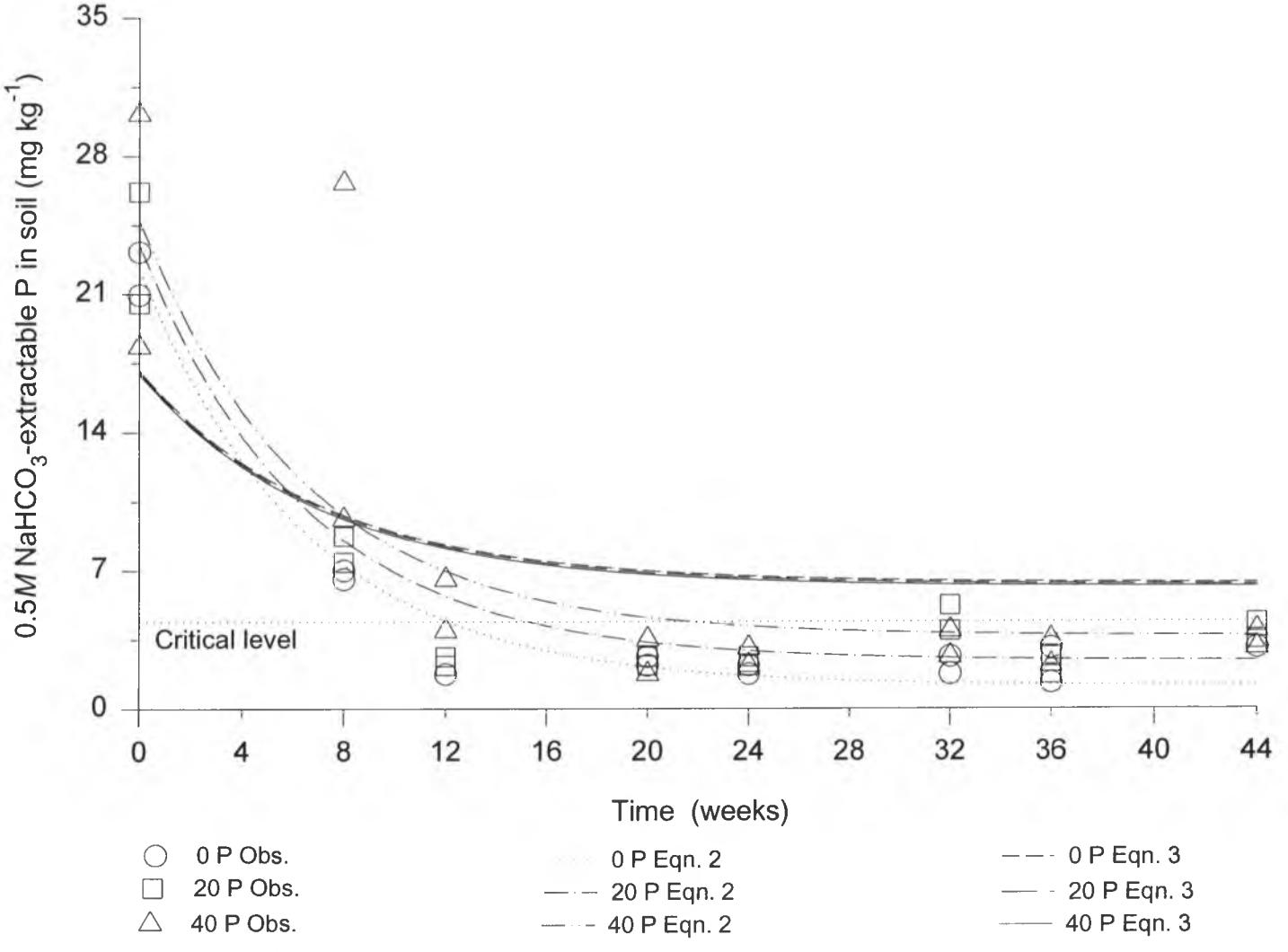


Figure 32. Observed and predicted 0.5*M* $NaHCO_3$-extractable P of Serang soil with rice crops.

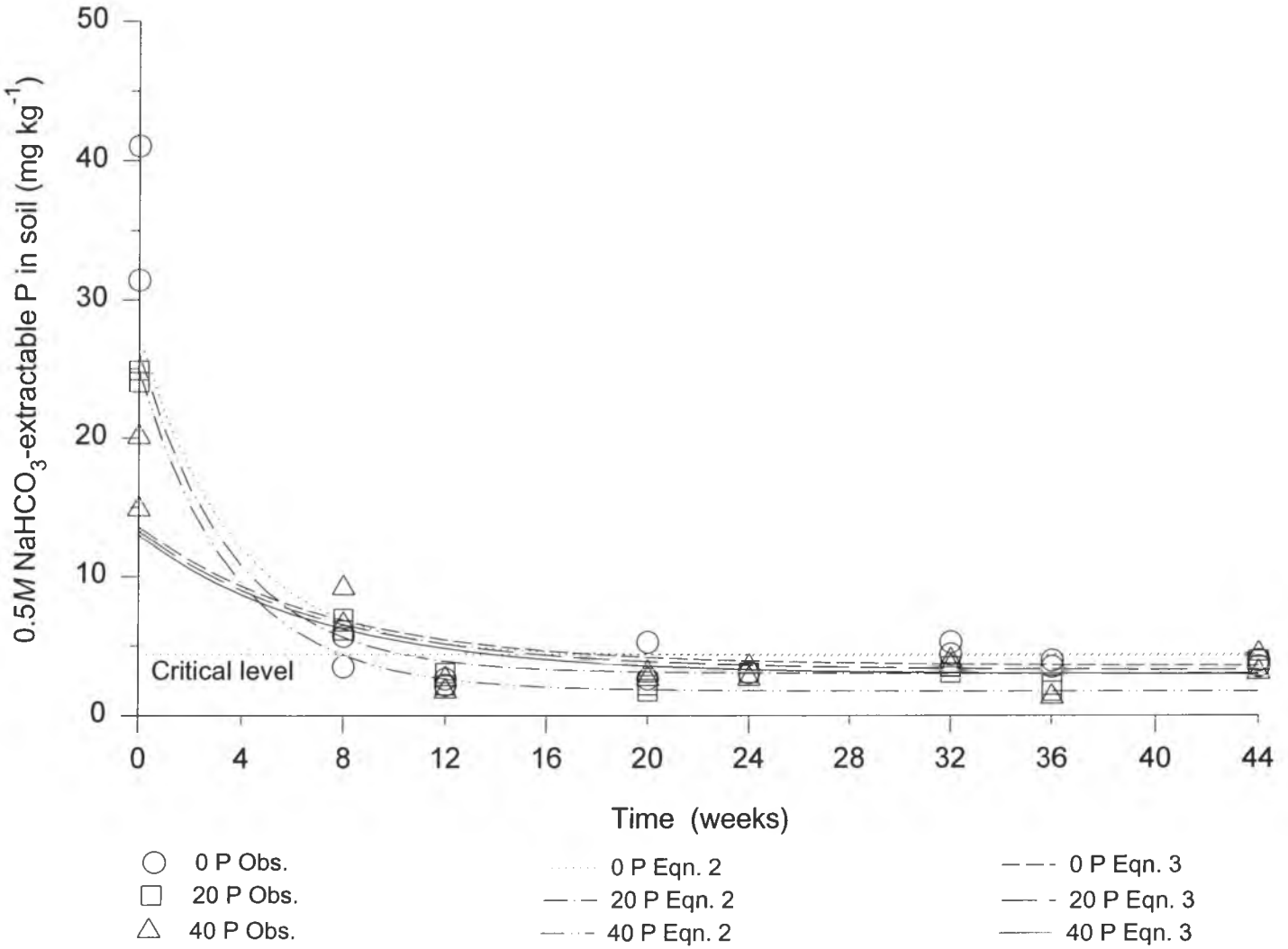


Figure 33. Observed and predicted 0.5*M* $NaHCO_3$-extractable P of Kerawang soil with rice crops.

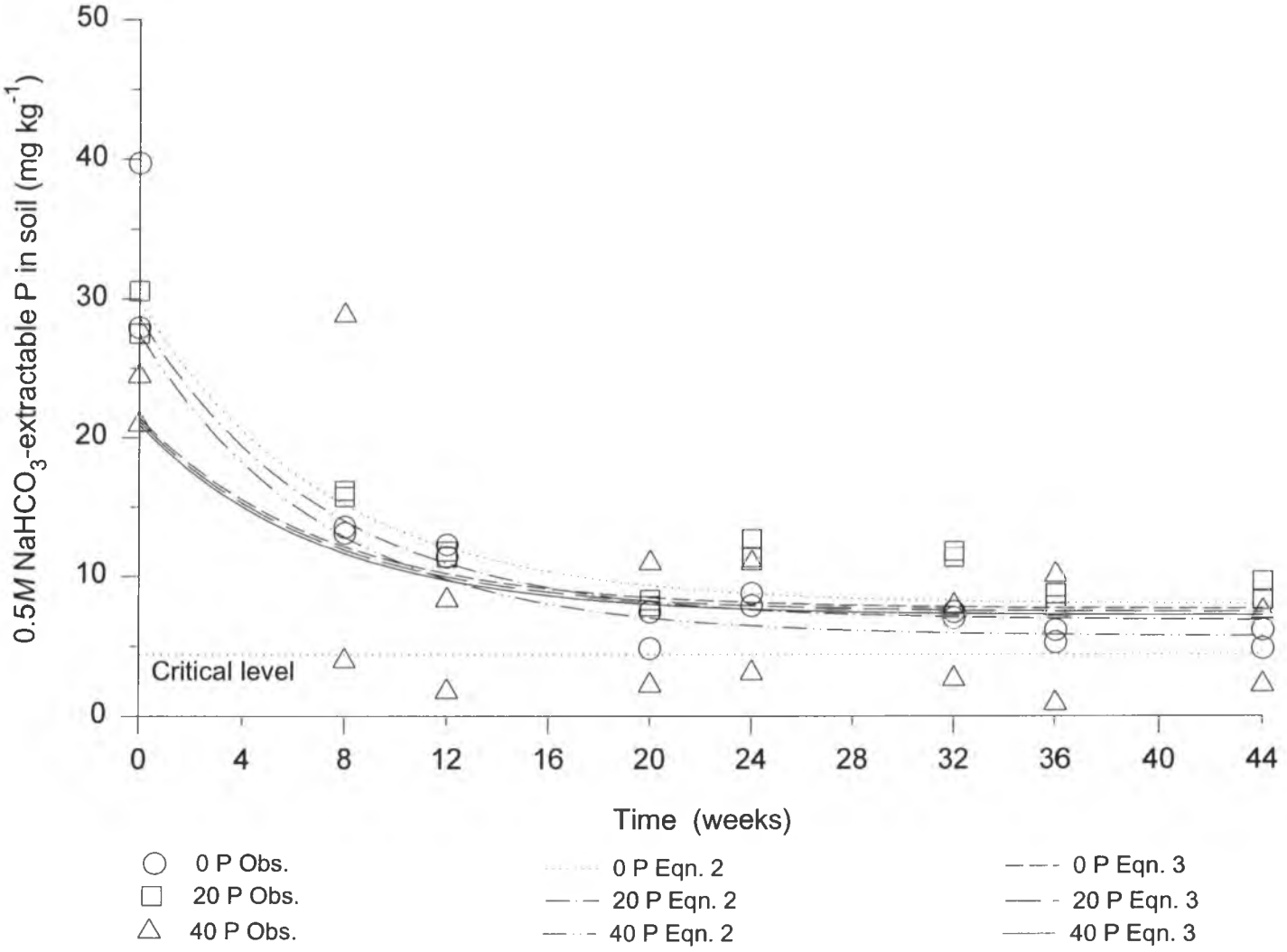


Figure 34. Observed and predicted 0.5*M* $NaHCO_3$-extractable P of Brebes soil with rice crops.

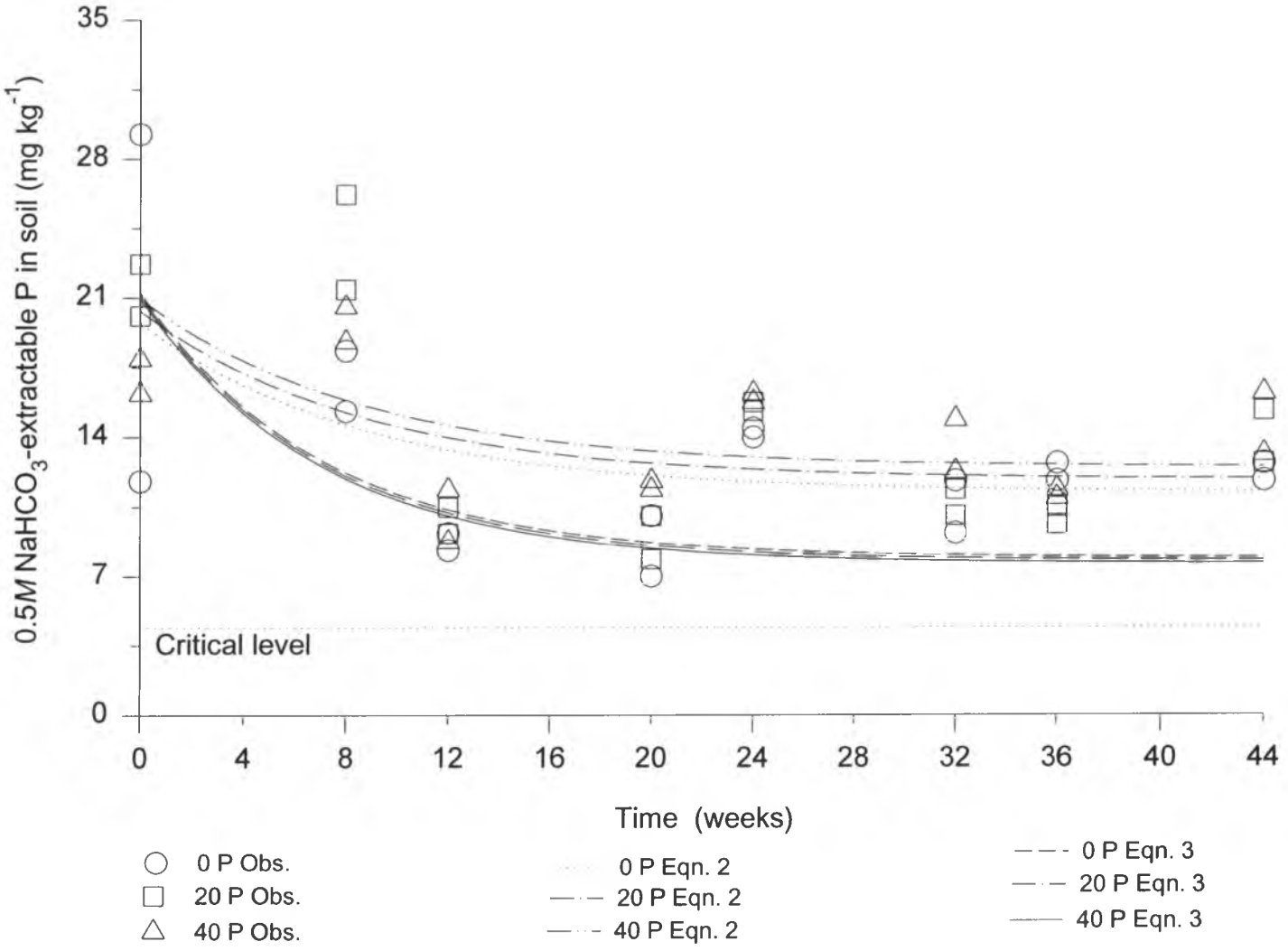


Figure 35. Observed and predicted 0.5*M* $NaHCO_3$-extractable P in Silo soil with rice crops.

Model 1b for the experiment with rice revealed that clay content played an important role in the linear part of the model, whereas soil pH and clay physical activity performed an important function on the nonlinear part of the model, defining the rate of decline. Similar to model 1a (predicting 0.5*M* $NaHCO_3$-extractable P without rice), model 1b revealed that the higher the clay physical activity the more rapid the decrease in extractable P, especially during early crops, which was clearly shown in the nonlinear portion of the graphical model (Figures 32 to 35).

Likewise, on the linear part of the model, clay physical activity and clay content negatively influenced 0.5*M* $NaHCO_3$-extractable P. The higher the clay content and clay physical activity of the soils the lower the 0.5*M* $NaHCO_3$-extractable P at any given time. The effect of clay content was slightly different compared with the linear correlation between clay content and 0.5*M* $NaHCO_3$-extractable P, which was positively correlated (r = 0.182), see Table 9. This was perhaps because in this model clay interacted with P, which indicated that the higher the clay content the higher the amount of P applied held by clay and caused the final amount of 0.5*M* $NaHCO_3$-extractable P decreased.

As shown in Figures 32 to 35 (also Figures 74 to 79 in the Appendix C.), predicted 0.5*M* $NaHCO_3$-extractable P did not decline below the critical level of 4.4 mg P kg^{-1} at least to 4 crops and speculatively up to 8 crops, except in the Kerawang (Figure 33), Mojokerto (Figure 78), and Jenggawah (Figure 79) soils. For Kerawang and Mojokerto soils, the predicted 0.5*M* $NaHCO_3$-extractable P declined below the

critical level shortly after the first crop, whereas for Jenggawah soil, it declined below the critical level after the second crop. These declines might be induced by their relatively high clay activities which would reduce 0.5*M* $NaHCO_3$-extractable P more rapidly.

Both final models include different soil properties as the model's variables (soil pH, soil organic carbon, clay content, and clay physical activity) , except that they had the same soil property as the nonlinear variable, which was clay physical activity. The difference in the model variables could not be explained clearly.

In general, the measured data and the predicted 0.5*M* $NaHCO_3$-extractable P from the no-rice treatments declined less rapidly compared to soils where rice was present. The relatively more rapid decline of extractable P in the presence of rice occurred at the first crop and curved into a gradual decline (possibly approaching a constant value) thereafter. This rapid decline was most likely caused by plant uptake.

4. 4. 2. Predicting Change in HCl-extractable P

The results of the linear correlation analyses between 25% HCl-extractable P for both experiments with and without rice with some physical and chemical soil properties showed that all soil properties measured in this study showed significant to highly significant correlation with 25% HCl-extractable P, except for the ammonium oxalate extractable aluminum. All of the measured soil properties were correlated positively with HCl-extractable P, except for clay physical activity which was negatively correlated (Table 14).

Table 14. Coefficient of correlation of 25% HCl-extractable P with soil properties.

Soil Properties	Coefficient of Correlation	
	Experiment without rice	Experiment with rice
pH	0.420^{**}	0.429^{**}
Clay content	0.585^{**}	0.559^{**}
15 bar %moisture	0.318^{**}	0.311^{**}
Plasticity Index	0.316^{**}	0.307^{**}
Clay physical activity	-0.748^{**}	-0.702^{**}
Soil surface area	0.336^{**}	0.338^{**}
Clay surface area	0.367^{**}	0.351^{**}
Organic carbon	0.245^{**}	0.250^{**}
Calcium carbonate	0.603^{**}	0.585^{**}
Ammonium Oxalate Fe	0.141^{**}	0.111^{*}
Ammonium Oxalate Al	0.016^{ns}	-0.011^{ns}
Initial HCl-extractable P	0.958^{**}	0.920^{**}

The degrees of freedom = 478; r(478; 0.01) = 0.118; r(478; 0.05) = 0.090
^{ns}) Non significant; *) significant; and **) highly significant.

The results of fitting the empirical model of equation [2] to HCl-extractable P data of the experiment without and with rice are shown in Tables 15 and 16, respectively. The results of fitting the site-specific model of equation [3] to HCl-extractable P of both experiments are shown in Tables 17 and 18, respectively.

Table 15. Parameters of fitting equation [2] to 25% HCl-extractable P of the without rice experiment.

Soil/Location	b0	t-value	b1	t-value	b2	t-value	k	t-value	RSE†
Serang	92.5	32.3	0.484	5.05	22.8	4.67	0.205	1.61	10.8
Cianjur	434.4	33.4	0.996	3.27	0.28	0.09	-0.089	-0.34	34.5
Kerawang	201.5	17.5	0.559	4.80	44.2	4.22	0.046	1.70	13.2
Brebes	183.0	4.4	0.355	1.42	56.7	1.51	0.034	0.71	28.3
Purbalingga	172.0	6.9	0.573	3.73	34.8	1.55	0.035	0.73	17.4
Purwodadi	528.8	38.2	0.341	0.73	0.003	0.08	-0.224	-0.76	53.0
Madiun	401.1	57.5	0.396	1.84	0.049	0.16	-0.144	-1.02	24.3
Mojokerto	123.8	10.8	0.355	1.50	0.97	0.25	-0.078	-0.90	26.8
Silo	317.7	8.8	0.300	1.56	20.2	0.61	0.032	0.30	21.7
Jenggawah	271.4	47.1	0.778	5.11	31.2	3.93	0.105	1.61	17.2

†) Residual Standard Error of the model.

Equations were estimated from 48 observations. t(44; 0.05) = 2.017; t(44; 0.01) = 2.695.

The model of equation [2] is: $EP_t = b0 + b1\ P + b2\ Exp(-k\ Time)$.

Table 16. Parameters of fitting equation [2] to 25% HCl-extractable P of the experiment with rice.

Soil/Location	b0	t-value	b1	t-value	b2	t-value	k	t-value	RSE†
Serang	48.4	9.23	0.293	3.29	73.0	13.5	0.066	5.09	10.1
Cianjur	116.6	0.018	0.505	2.32	303.7	0.047	0.002	0.05	24.7
Kerawang	130.5	6.03	0.396	3.22	126.7	6.44	0.033	3.11	13.9
Brebes	168.5	44.7	0.464	4.65	92.2	17.7	0.105	7.27	11.3
Purbalingga	130.9	9.38	0.211	1.38	86.2	6.74	0.049	2.66	17.4
Purwodadi	553.9	19.8	0.048	0.123	-10.1	-0.631	-0.057	-1.73	43.8
Madiun	410.5	5.26	0.416	2.05	-23.5	-0.326	-0.022	-0.511	22.9
Mojokerto	102.3	24.3	0.273	1.91	60.1	8.29	0.238	2.50	16.2
Silo	280.0	15.7	-0.471	-0.815	193.6	6.57	0.174	2.51	65.3
Jenggawah	250.1	22.5	-0.136	-0.362	196.7	10.3	0.231	3.20	42.6

†) Residual Standard Error of the model.

Equations were estimated from 48 observations. t(44; 0.05) = 2.017; t(44; 0.01) = 2.695.

The model of equation [2] is: $EP_t = b0 + b1\ P + b2\ Exp(-k\ Time)$.

4. 4. 2. 1. Experiment without Rice

The best two models, model 1c and 2c, which were selected from hundreds of models tested by nonlinear regression analysis, are shown in Table 17. Model 1c carried smaller residual standard error (RSE) by 0.5401 compared to model 2c. Model 1c, however, involved five soil variables, while model 2c comprised only four soil variables in the model.

Model 2c consisted of initial HCl-extractable P (EP_i), soil organic carbon (OC), clay content (CLAY), and clay physical activity (CAT), whereas model 1c had the same variables with an additional variable, ammonium oxalate extractable iron (FE) (on the interaction with added fertilizer P). This implied that for routine application model 1c may be too costly because the Fe analysis is time consuming. Therefore, model 2c would be considered as the best model for predicting the change of HCl-extractable P of soils without the existence of rice crops, because it incorporated fewer soil properties and would cost less for soil analysis.

The graphical presentations of the empirical model of equation [2] and the soil specific model of equation [3] along with the observed data indicated that unlike the predicted 0.5*M* $NaHCO_3$-extractable P, the predicted HCl-extractable P declined gradually up to fourth crop, see Figures 36 to 39 (and Figures 80 to 85 in the Appendix D). In fact, for some soils, Cianjur, Purwodadi, and Madiun (Figures 80, 82, and 83 in Appendix D), predicted HCl-extractable P inclined gradually with time.

Table 17. Results on fitting of equation [3] to 25% HCl-extractable P of experiment with no rice.

Model 1c	Parameters (Soil variables)							
	a EP_i	P_{eq}	b OC	c FE P	d CLAY $e^{\{...\}}$	k0	k1 CAT	RSE†
Coefficient:	0.6628	0.0000	37.2313	16.9951	0.6777	-0.1748	0.3045	32.771
t-value:	36.7097**	0.0000	16.4154**	6.9074**	6.9221**	-5.1823**	4.8851**	
Equation:	$EP_t = (0.6628\ EP_i - 0.0) + (37.2313\ OC) + (16.9951\ FE\ P) + \{0.6777\ CLAY\ e^{\{-(-0.1748+0.3045\ CAT)\ Time\}}\}$							
Model 2c‡	a EP_i	P_{eq}	b OC	c OC P	d CLAY $e^{\{...\}}$	k0	k1 CAT	RSE†
Coefficient:	0.6482	0.0000	36.2229	0.2853	0.8156	-0.1477	0.2558	33.3111
t-value:	35.8287**	0.0000	14.7726**	5.5844**	8.3840**	-6.1788**	5.8275**	
Equation:	$EP_t = (0.6482\ EP_i - 0.0) + (36.2229\ OC) + (0.2853\ OC\ P) + \{0.8156\ CLAY\ e^{\{-(-0.1477+0.2558\ CAT)\ Time\}}\}$							

Equations were estimated from 480 observations. The t(473; 0.05) = 1.960; t(473; 0.01) = 2.576.

†) Residual Standard Error of the model.

‡) Selected as the prediction model and for the final plot.

ns) = non significant; *) = significant; **) = highly significant.

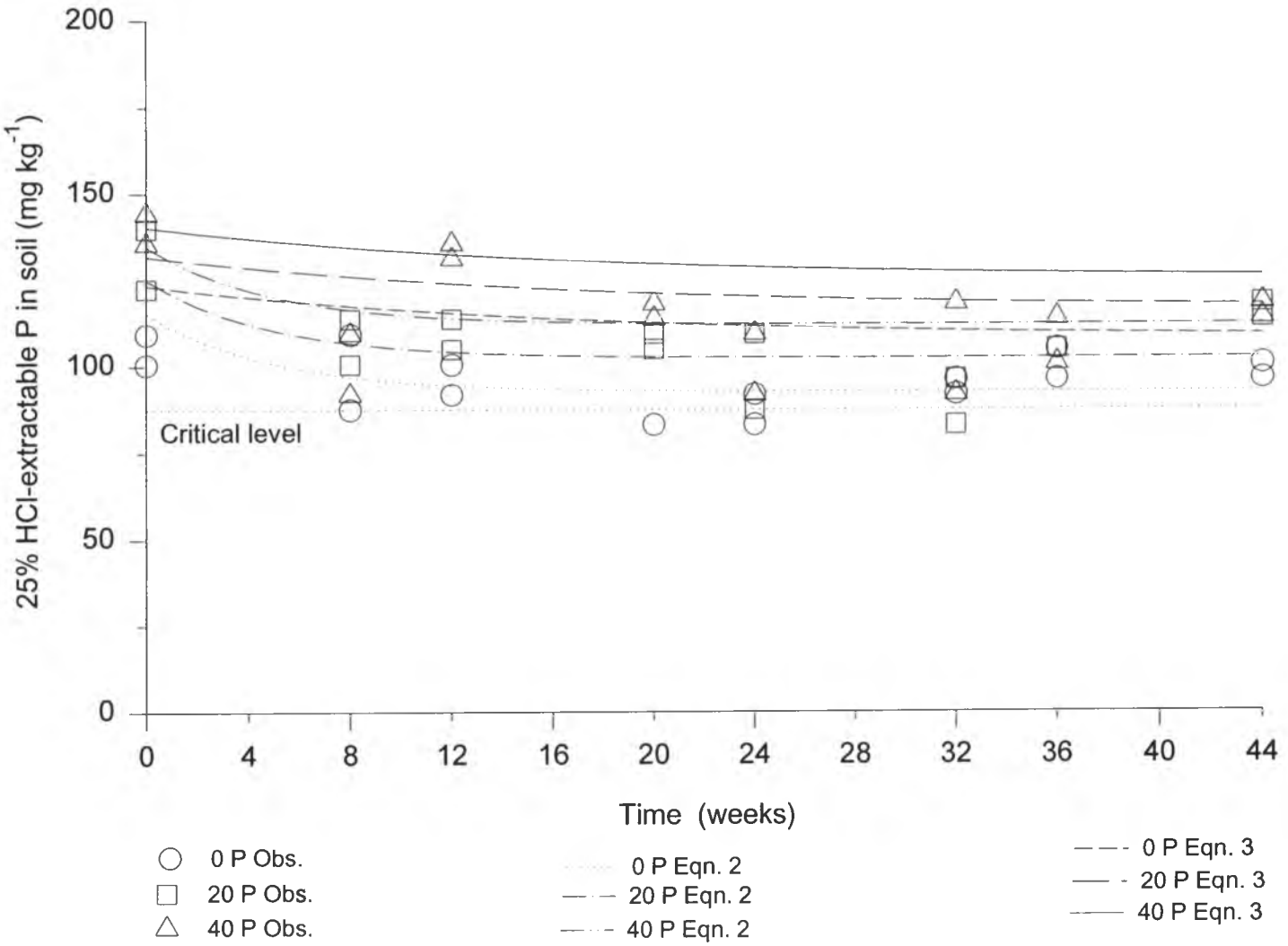


Figure 36. Observed and predicted HCl-extractable P of Serang soil without rice crops.

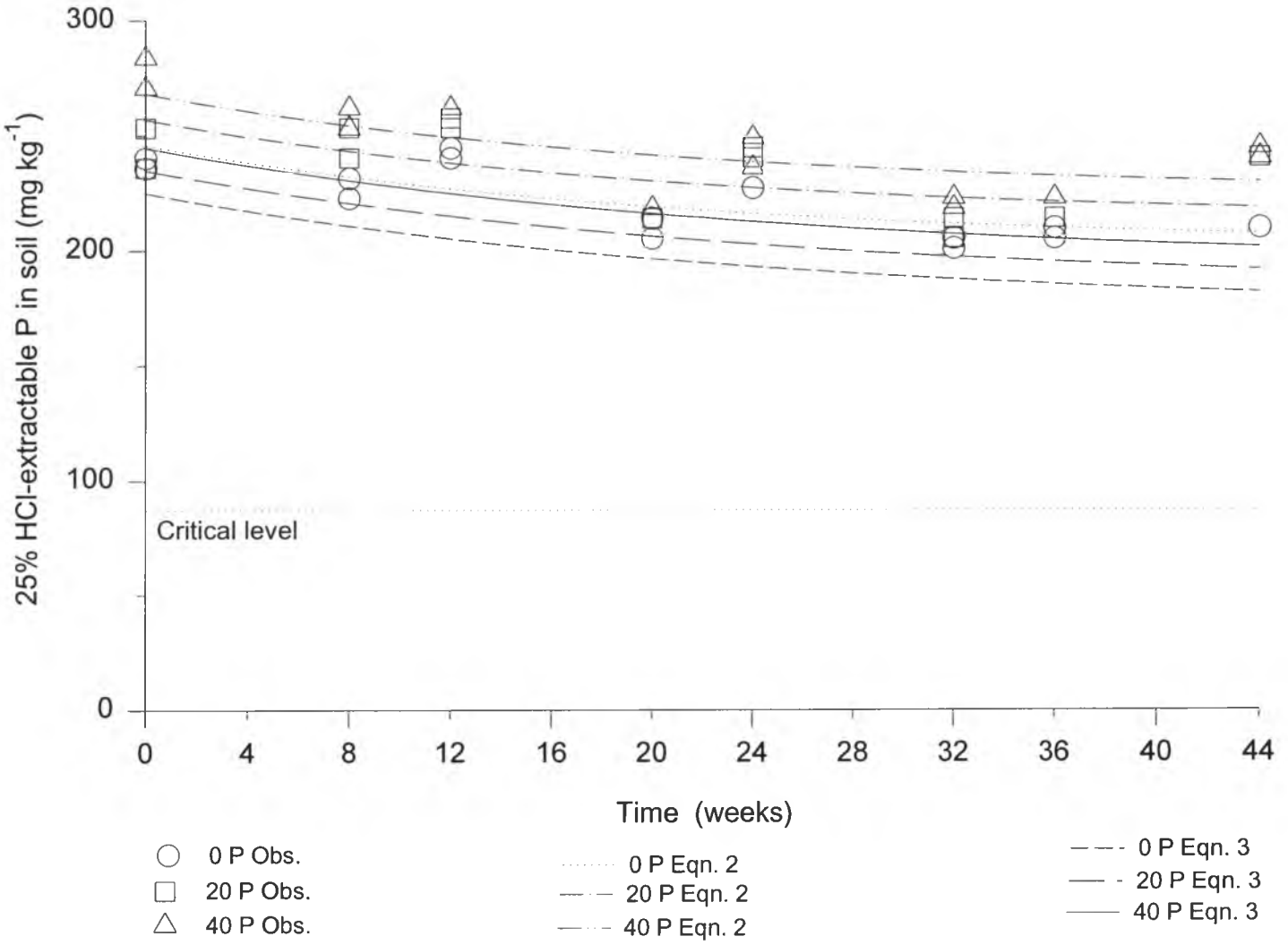


Figure 37. Observed and predicted HCl-extractable P of Kerawang soil without rice crops.

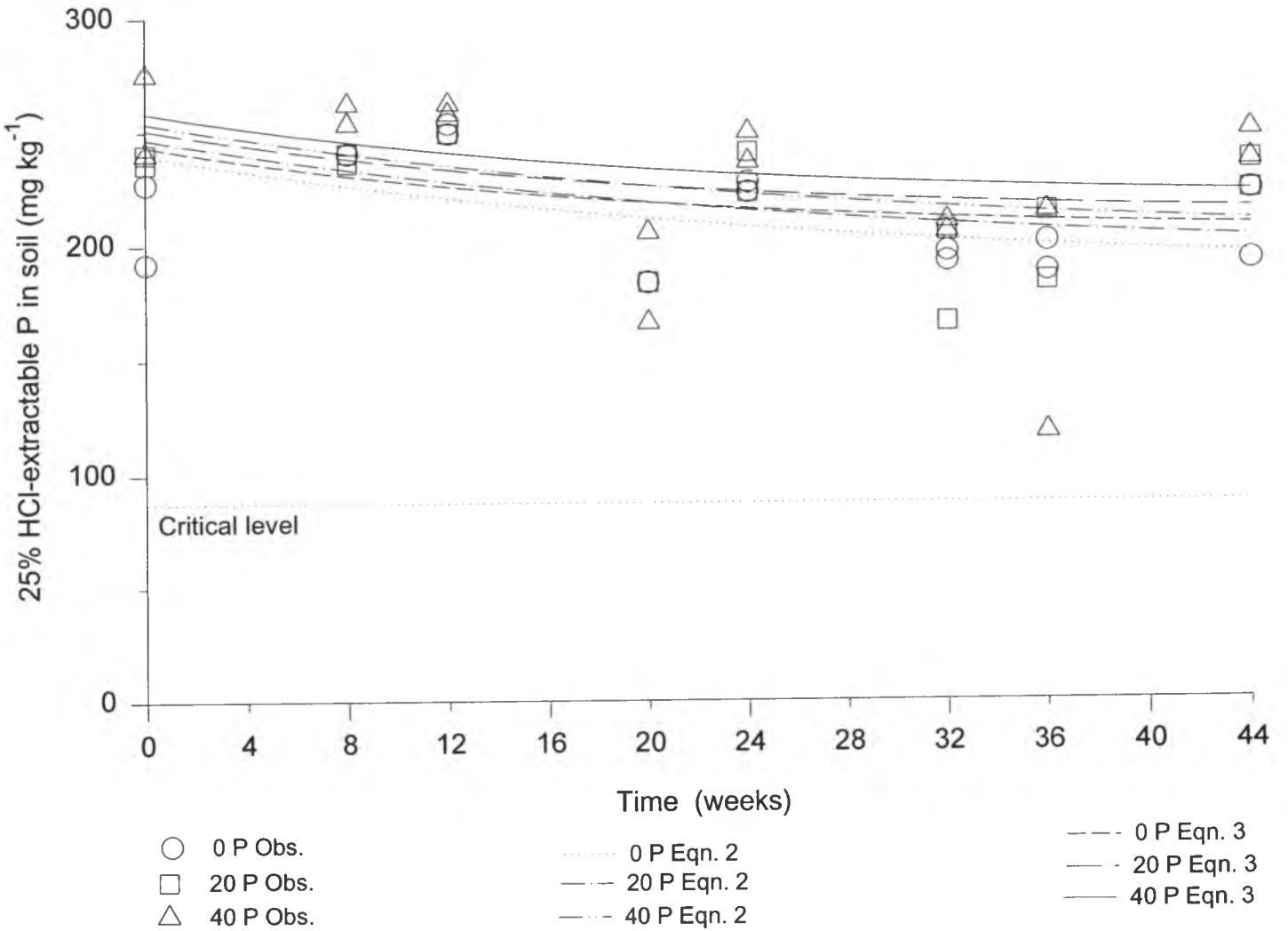


Figure 38. Observed and predicted HCl-extractable P of Brebes soil without rice crops.

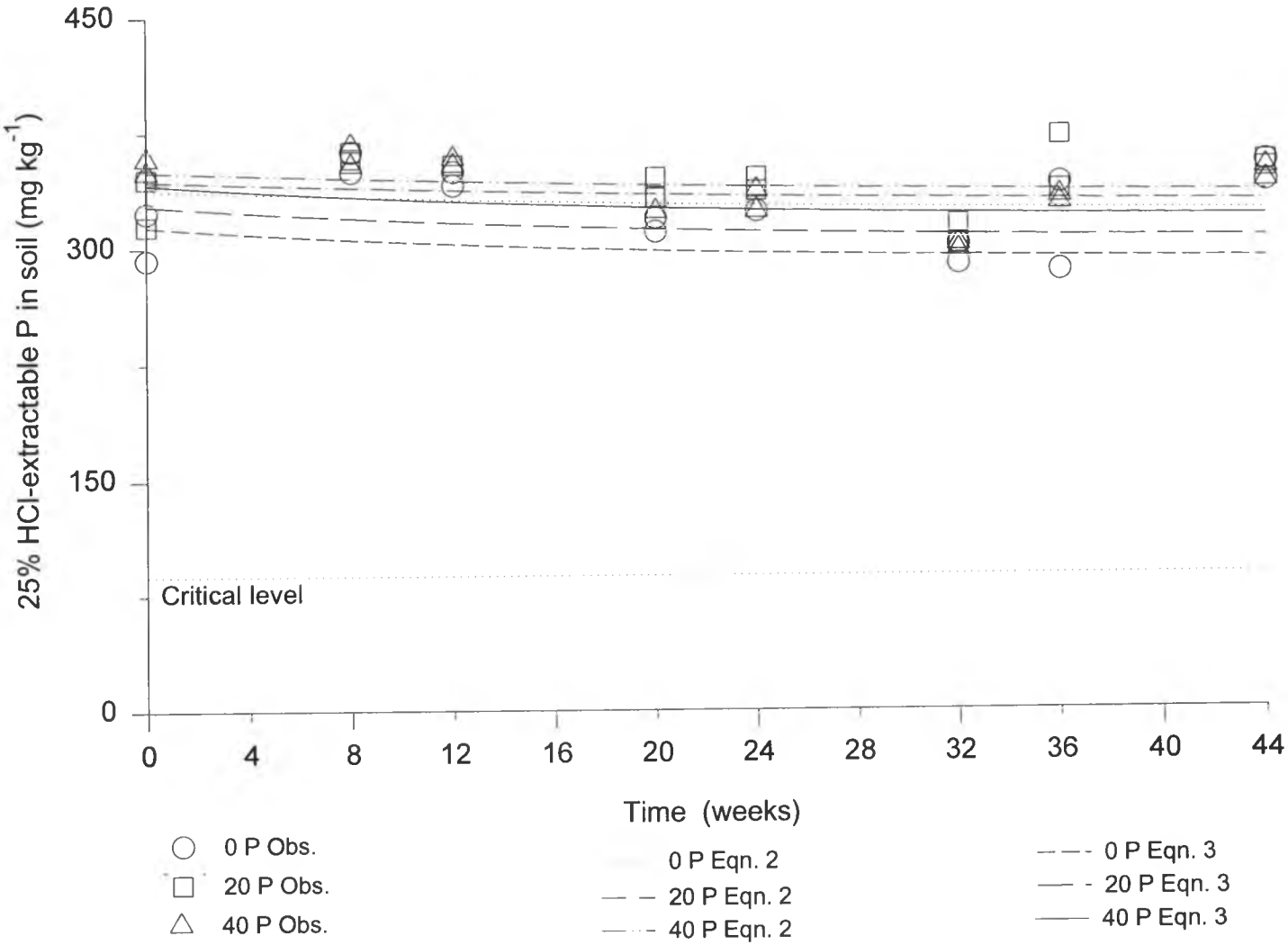


Figure 39. Observed and predicted HCl-extractable P of Silo soil without rice crops.

Model 2c shows that clay physical activity and clay content of the soils play an important role in the nonlinear portion of the model, whereas soil organic carbon performed an important role on the linear portion of the model. The higher the clay physical activity of the soil the greater the decrease in HCl-extractable P. On the other hand, the higher the organic carbon and clay content the higher the amount HCl-extractable P of that soil.

4. 4. 2. 2. Experiment with Rice

The best two models, models 1d and 2d, resulting from nonlinear regression analysis are listed in Table 18. Model 1d accounted for more variation that did model 2d. Model 1d, however, contained soil pH (PH), which was not included in model 2d. The four soil variables in both models were initial HCl-extractable P (HCLPI), soil organic carbon (OC), clay content (CLAY), and clay physical activity of the soil (CAT). For routine application model 2d might be preferable because it is simpler and its measurement should be less costly. Therefore, model 2d was designated as the best model for predicting the change in HCl-extractable P where rice crops are present.

The graphical presentations of HCl-extractable P using empirical model of equation [2] prediction, and with the selected model 2d indicated that predicted HCl-extractable P decreased rapidly for the first two crops (up to end of second crop), then declined asymptotically approaching a constant value, see Figures 40 to 43 (and Figures 86 to 91 in the Appendix E).

Table 18. Results on fitting of equation [3] to 25% HCl-extractable P of experiment with rice.

Model 1d	Parameters (Soil Variables)							
	a EP_i	P_{eq}	b OC	c CLAY P	d pH $e^{\{...\}}$	k0	k1 CAT	RSE†
Coefficient:	0.5726	43.9323	49.5374	0.0063	20.8429	-0.1938	0.3862	39.5898
t-value:	26.7268**	5.3108**	12.6724**	3.2240**	17.5817**	-6.2259**	6.6637**	
Equation:	$EP_t = \{0.5726\ EP_i - 43.9323\} + (49.5374\ OC) + (0.0063\ CLAY\ P)\} + \{20.8429\ pH\ e^{\{-(-0.1938+0.3862\ CAT)\ Time\}}\}$							
Model 2d‡	a EPi	P_{eq}	b OC	c CLAY P	d OC $e^{\{...\}}$	k0	k1 CAT	RSE†
Coefficient:	0.6712	11.6284	22.2617	0.0060	59.1277	-0.1438	0.3199	39.8271
t-value:	39.5542**	1.6990ns	5.5814**	3.0640**	17.4455**	-4.2761**	5.1427**	
Equation:	$EP_t = \{0.6712\ EP_i - 11.6284\} + (22.2617\ OC) + (0.0060\ CLAY\ P) + \{59.1277\ OC\ e^{\{-(-0.1438+0.3199\ CAT)\ Time\}}\}$							

Equations were estimated from 480 observations. The t(473; 0.05) = 1.960; t(473; 0.01) = 2.576.

†) Residual Standard Error of the model.

‡) Selected as the prediction model and for the final plot.

ns) = non significant; *) = significant; **) = highly significant.

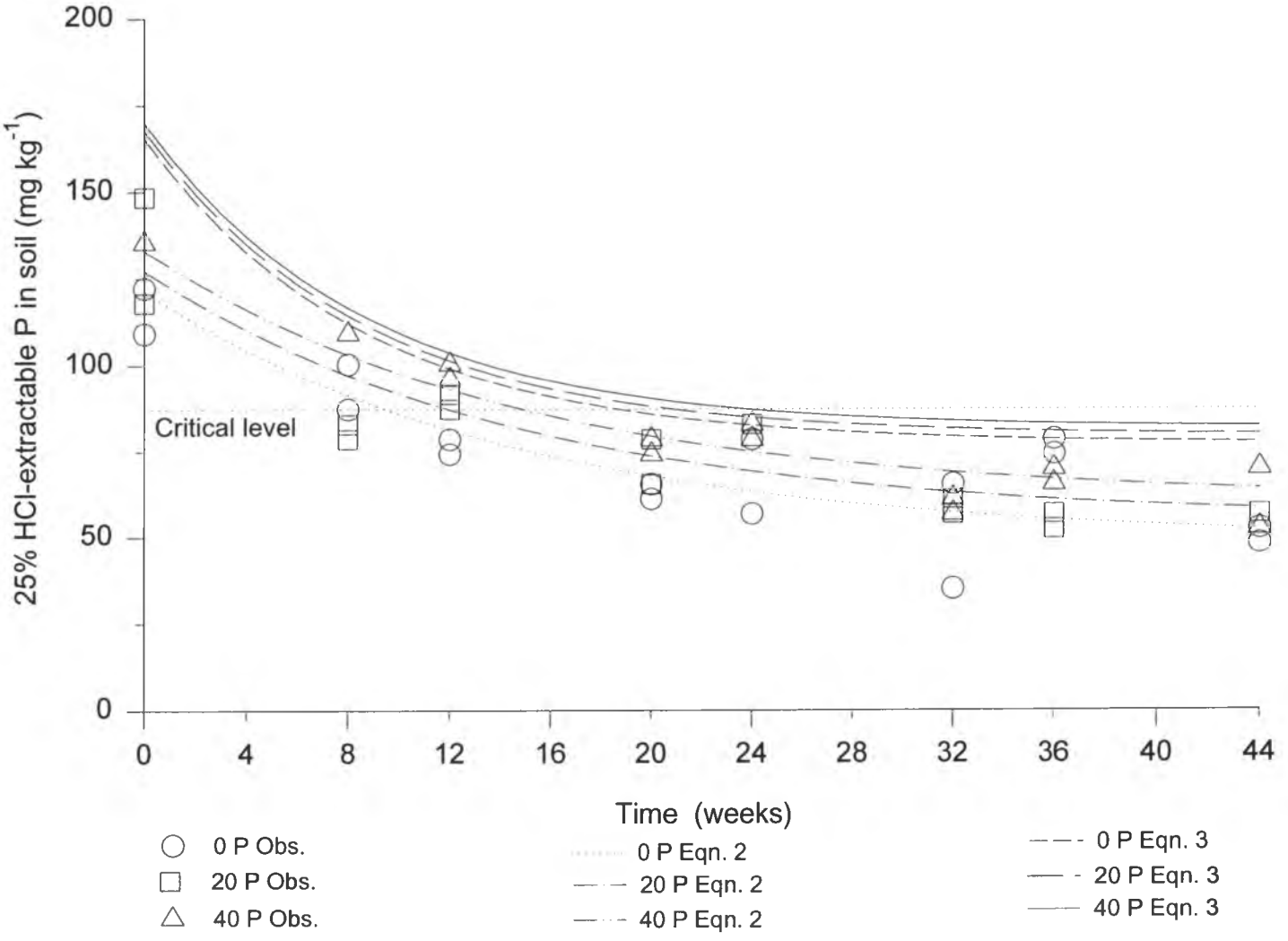


Figure 40. Observed and predicted HCl-extractable P of Serang soil with rice crops.

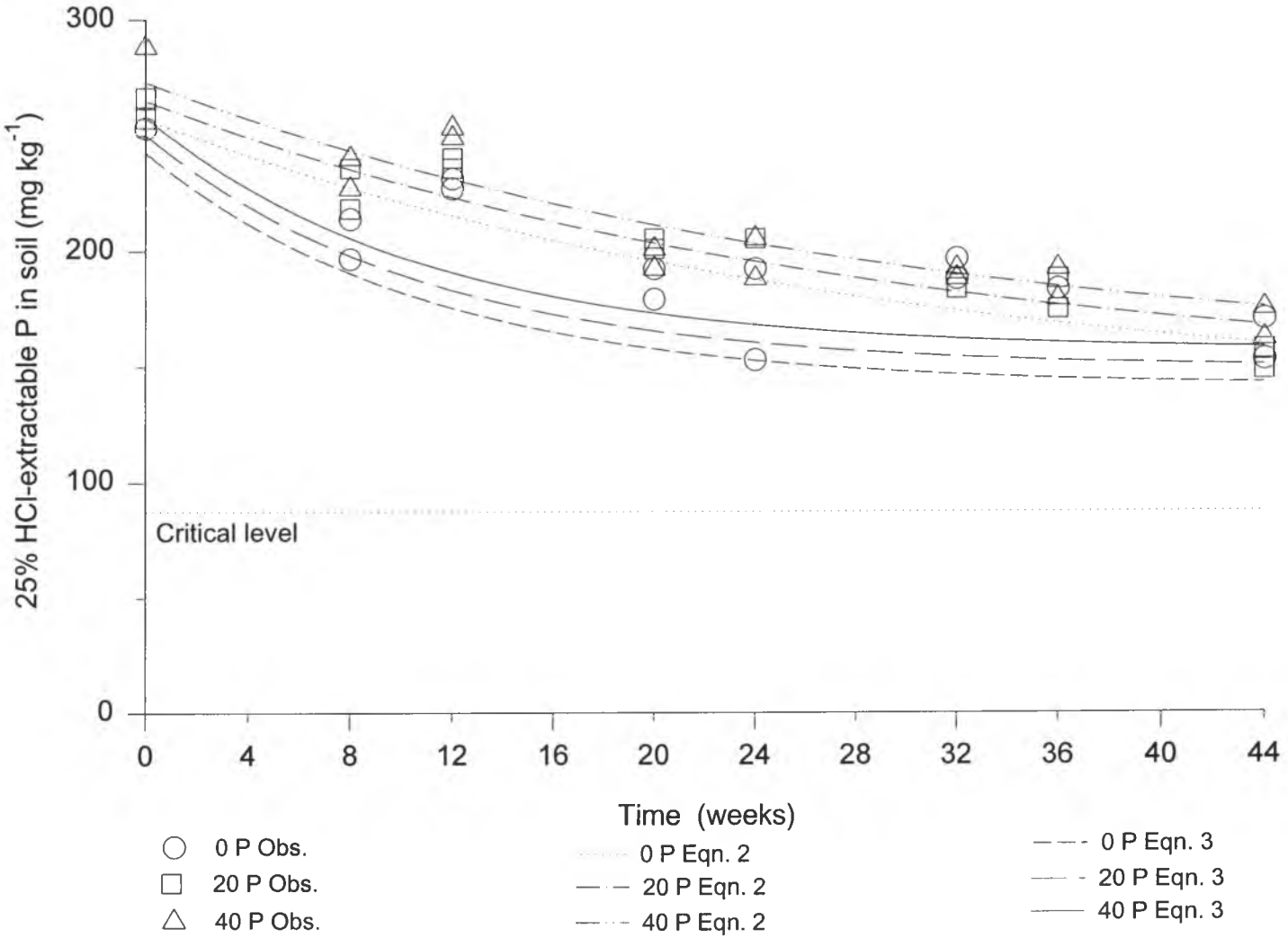


Figure 41. Observed and predicted HCl-extractable P of Kerawang soil with rice crops.

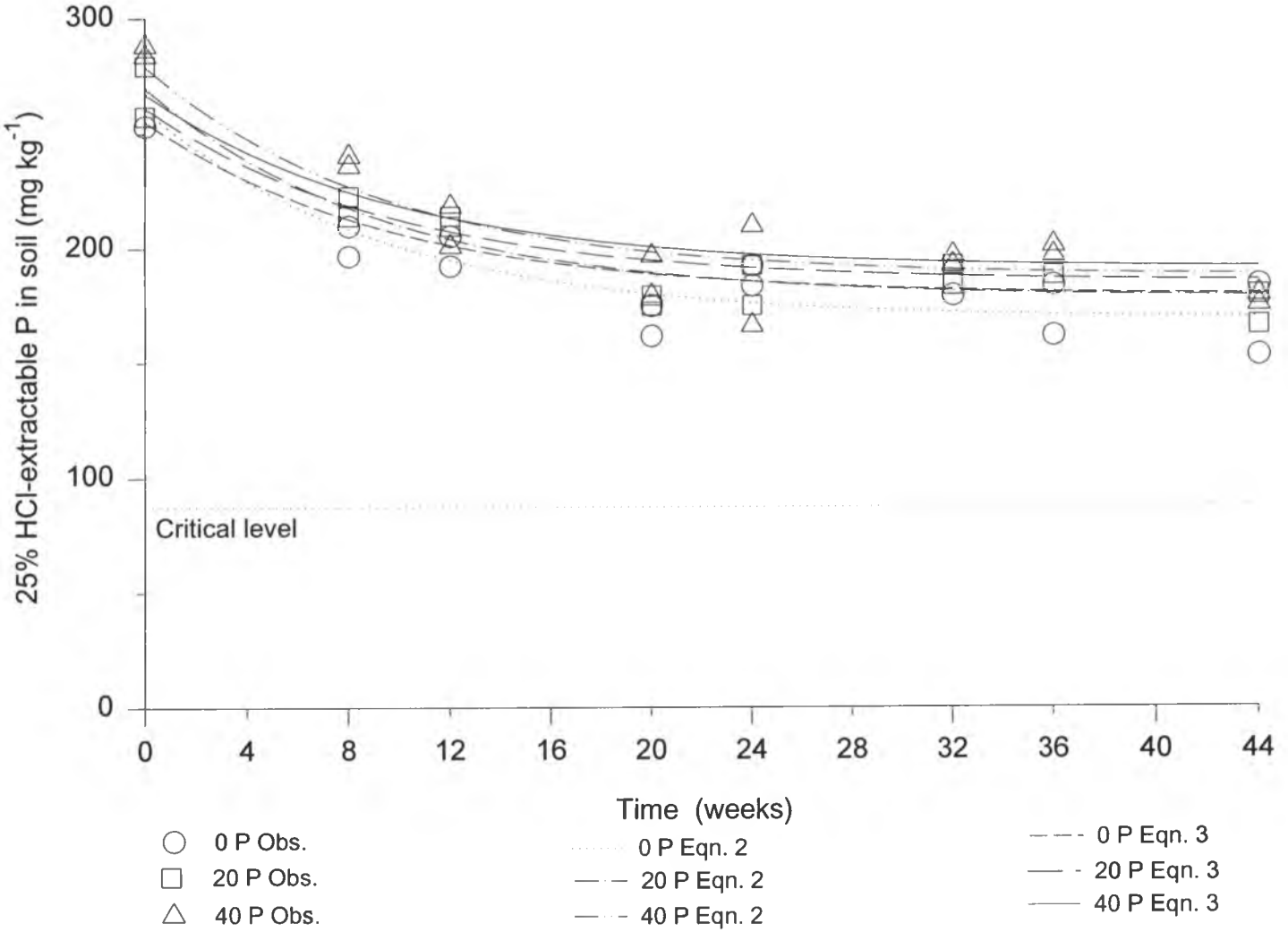


Figure 42. Observed and predicted HCl-extractable P of Brebes soil with rice crops.

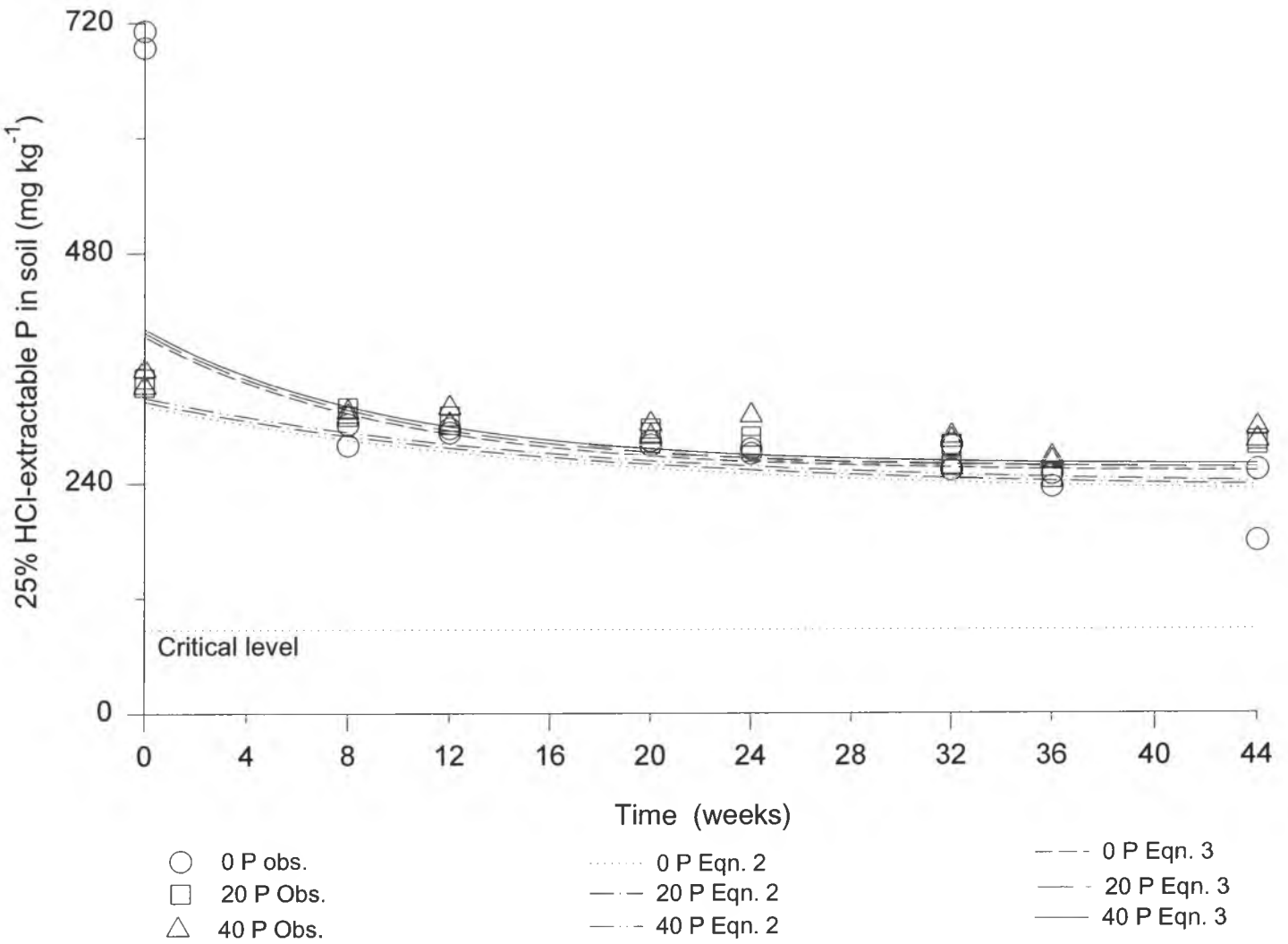


Figure 43. Observed and predicted HCl-extractable P of Silo soil with rice crops.

Model 2d revealed that clay physical activity performed an important role in the nonlinear part of the model, whereas organic carbon and clay content were important in the linear portion of the model. Similar to model 2c (for predicting HCl-extractable P for condition without rice crops), this model also indicated that the higher the clay physical activity of the soils the more rapid the decrease in HCl-extractable P. On the contrary, the higher the clay and organic carbon contents of the soil the higher the amount of HCl-extractable P.

As shown in Figures 40 to 43 (and Figures 86 to 91 in the Appendix E), the predicted change of HCl-extractable P for most of the studied soils did not decline below the critical level of 87.3 mg kg^{-1} (Moersidi *et al.*, 1989) for at least up to four crops, except for Serang soil. The initial HCl-extractable P of Serang soil was originally below the critical level, and had very low in clay content, 19%. The Serang soil also has the highest clay physical activity.

In general, similar to the 0.5*M* $NaHCO_3$-extractable P, the predicted HCl-extractable P declined less rapidly where there were no rice crops than where rice crops were present. This slower decline in HCl-extractable P was probably caused by flooding during planting seasons. Flooding the soils increases the availability of both native and added P (Patrick and Mahapatra, 1968; Ponnamperuma, 1985).

The more rapid decline of extractable P in the presence of rice crops occurred during the first crop and curved into a gradual decline there after. This rapid decline was most likely caused by crop uptake.

The prediction models that were developed from this study, especially those that predict the change in extractable P in the presence of rice crops, might be employed to improve the site specific management in paddy soils of Java. These prediction models could be implemented in GIS applications to reveal the results in a digital map format, which may be easier to understand and interpret.

The prediction models developed for both methods of P extractions, $0.5M$ $NaHCO_3$ and 25% HCl, were equally satisfactory. Therefore, both prediction models developed could be used depending upon the availability of the soil data required for the models.

4. 5. Predicting Desorption of Residual P

Desorption of residual P is defined as the movement of P from the residual P pool to the extractable P pool (F3 upward arrow in Figure 7). The way it was measured, however, was actually the net desorption, which was the net difference between F3 and F2 of the phosphorus diagram in Figure 7. In this study, there were two ways of measuring the net desorption: a) the total desorption (TD), and b) the net desorption (ND).

4. 5. 1. Total Desorption (TD)

The total desorption (TD) of residual P was obtained by taking the difference between the crop uptake P (CUP) with the difference between extractable P obtained from the soil without and with the presence of crops. It was expressed in equation [4] of the Materials and Methods as:

$TD_t = CUP_t - (EP_t^{-C} - EP_t^{+C})$ [equation 4 of Chapter 3],

where CUP_t is the cumulative amount of P was taken by the crop at time t, EP_t^{-C} is the extractable P at time t measured from the soils where rice was not grown, and EP_t^{+C} is the extractable P at time t measured from the soils where rice was grown.

4. 5. 1. 1. Total Desorption of 0.5*M* $NaHCO_3$ residual P (TD of 0.5*M* $NaHCO_3$-P)

The total desorption (TD) of 0.5*M* $NaHCO_3$-P at any time, t, was calculated using equation [4]. The coefficients of linear correlation between total desorption of 0.5*M* $NaHCO_3$-residual P with some physical and chemical soil properties of all soils representative are listed in Table 19.

Table 19. Coefficient of correlation between total desorption (TD) of 0.5*M* $NaHCO_3$-residual P with some soil properties.

Soil Properties	Correlation Coefficient of total desorption of 0.5*M* $NaHCO_3$-residual P:
pH	-0.272^{**}
Clay content	-0.071^{ns}
15 bar %moisture	-0.102^{ns}
Plasticity Index	-0.040^{ns}
Clay physical activity	0.057^{ns}
Soil surface area	-0.014^{ns}
Clay surface area	-0.198^{**}
Organic carbon	0.337^{**}
Calcium carbonate	-0.253^{**}
Ammonium Oxalate Fe	0.249^{**}
Ammonium Oxalate Al	0.178^{**}
Initial 0.5*M* $NaHCO_3$ extractable P	-0.075^{ns}

The degrees of freedom = 298; the r(298; 0.01) = 0.148; r(298; 0.05) = 0.113
^{ns}) Non significant; *) significant; and **) highly significant.

The correlation coefficients showed that soil pH (PH), surface area of the clay fraction (CA), soil organic carbon (OC), calcium carbonate content ($CaCO_3$), ammonium oxalate extractable iron (FE) and aluminum (AL) were significantly related to Total desorption of 0.5*M* $NaHCO_3$-P. Therefore, all of these variables were later considered in the process of selecting the best model for predicting the total desorption (TD) of 0.5*M* $NaHCO_3$ residual P. The results of fitting the empirical model of equation [5] to the calculated total desorption of 0.5*M* $NaHCO_3$-P values are presented in Table 20. Results of fitting the site specific model of equation [6] to total desorption of 0.5*M* $NaHCO_3$-residual P are shown in Table 21.

Table 20. Parameters of fitting the empirical model (equation [5]) to total desorption of 0.5*M* $NaHCO_3$-residual P.

Soil/Location	b0	b1	b2	k	RSE†
Serang	54.0	0.0487	-53.3	0.0347	4.88
Cianjur	96.7	0.114	-97.3	0.0326	4.73
Kerawang	304.9	0.177	-302.3	0.0041	4.21
Brebes	2641.0	-0.115	-2640.5	0.0004	7.59
Purbalingga	621.2	0.270	-627.4	0.0025	4.59
Purwodadi	23.4	-0.0188	-23.4	0.0313	6.09
Madiun	110.5	0.0208	-110.1	0.0111	3.54
Mojokerto	36.6	-0.0883	-34.7	0.0304	3.57
Silo	66.4	0.166	-68.2	0.0393	7.42
Jenggawah	67.4	0.0401	-67.6	0.0492	6.38

†) Residual Standard Error of the model.

Equations were estimated from 30 observations. The t(26; 0.05) = 2.056; t(26; 0.01) = 2.779.

The model of equation [5] is: $EP_t = b0 + b1\ P + b2\ Exp(k\ Time)$.

Table 21. Parameters of fitting the site specific model (equation [6]) to total desorption of 0.5*M* $NaHCO_3$-residual P.

Model 1e	Parameters of Soil variables						
	a EP_i	b OC	c FE P	d OC $e^{\{...\}}$	k0	k1 PH	RSE†
Coefficient:	-0.0919	61.6016	2.6037	-60.5950	-0.0421	0.0050	6.9873
t-value:	-2.6491*	6.7592**	3.8654**	-6.7758**	-4.3862**	4.1467**	
Equation:	$TD_t = (-0.0919\ EP_i) + (61.6016\ OC) + (2.6037\ FE\ P) + \{-60.5950\ OC\ e^{\{(-0.0421+0.0050\ PH)\ Time\}}\}$						
Model 2e‡	a EP_i	b OC	c CAT P	d OC $e^{\{...\}}$	k0	k1 PH	RSE†
Coefficient:	-0.0869	62.4036	0.0756	-61.2128	-0.0430	0.0052	7.1021
t-value:	-2.4529*	8.1181**	2.1696*	-8.1147**	-4.3127**	4.0810**	
Equation:	$TD_t = (-0.0869\ EP_i) + (62.4036\ OC) + (0.0756\ CAT\ P) + \{-61.2128\ OC\ e^{\{(-0.0430+0.0052\ PH)\ Time\}}\}$						

Equations were estimated from 300 observations. The t(293; 0.05) = 1.960; t(293; 0.01) = 2.576.

†) Residual Standard Error of the model.

‡) Selected as the prediction model and for the final plot.

ns) = non significant; *) = significant; **) = highly significant.

Two models are listed in Table 21, models 1e and 2e. Model 1e had smaller residual standard error by as much as 0.115 than that of model 2e. Both models had the same number of soil variables except one interaction between added P fertilizer and Fe content (FE) for model 1e and clay physical activity (CAT) for model 2e. Considering the time and cost for analyzing soil variables, however, model 2e is considerably simpler and less costly than model 1e. Therefore, for predicting the Total desorption of 0.5*M* $NaHCO_3$ residual P to residual extractable P model 2e is preferred. This model comprised of four soil variables, initial 0.5*M* $NaHCO_3$-extractable P (EP_i), soil organic carbon (OC), clay physical activity (CAT), and soil acidity (PH). Soil organic carbon and acidity were important in the nonlinear part of the model, whereas clay physical activity and soil organic carbon were important in the linear portion of the model.

Generally, the graphical presentation of the prediction model 2e, along with the empirical model (equation [5]) for all representative soils showed that 0.5*M* $NaHCO_3$ residual P desorbed relatively fast until the end of second crop then desorption slowed, see Figures 44 to 47 (also Figures 92 to 95 in the Appendix F). The prediction model also revealed that the higher the pH of the soil the less rapid the total desorption of 0.5*M* $NaHCO_3$ residual P. This result is consistent with the result of the negative correlation between total desorption of 0.5*M* $NaHCO_3$ residual P with soil pH. While the higher the organic carbon and clay physical activity of the soils

the higher the total desorption of 0.5*M* $NaHCO_3$ residual P to extractable P. These results also agreed with the positive correlation between total desorbed 0.5*M* $NaHCO_3$ residual P with organic carbon content and clay physical activity.

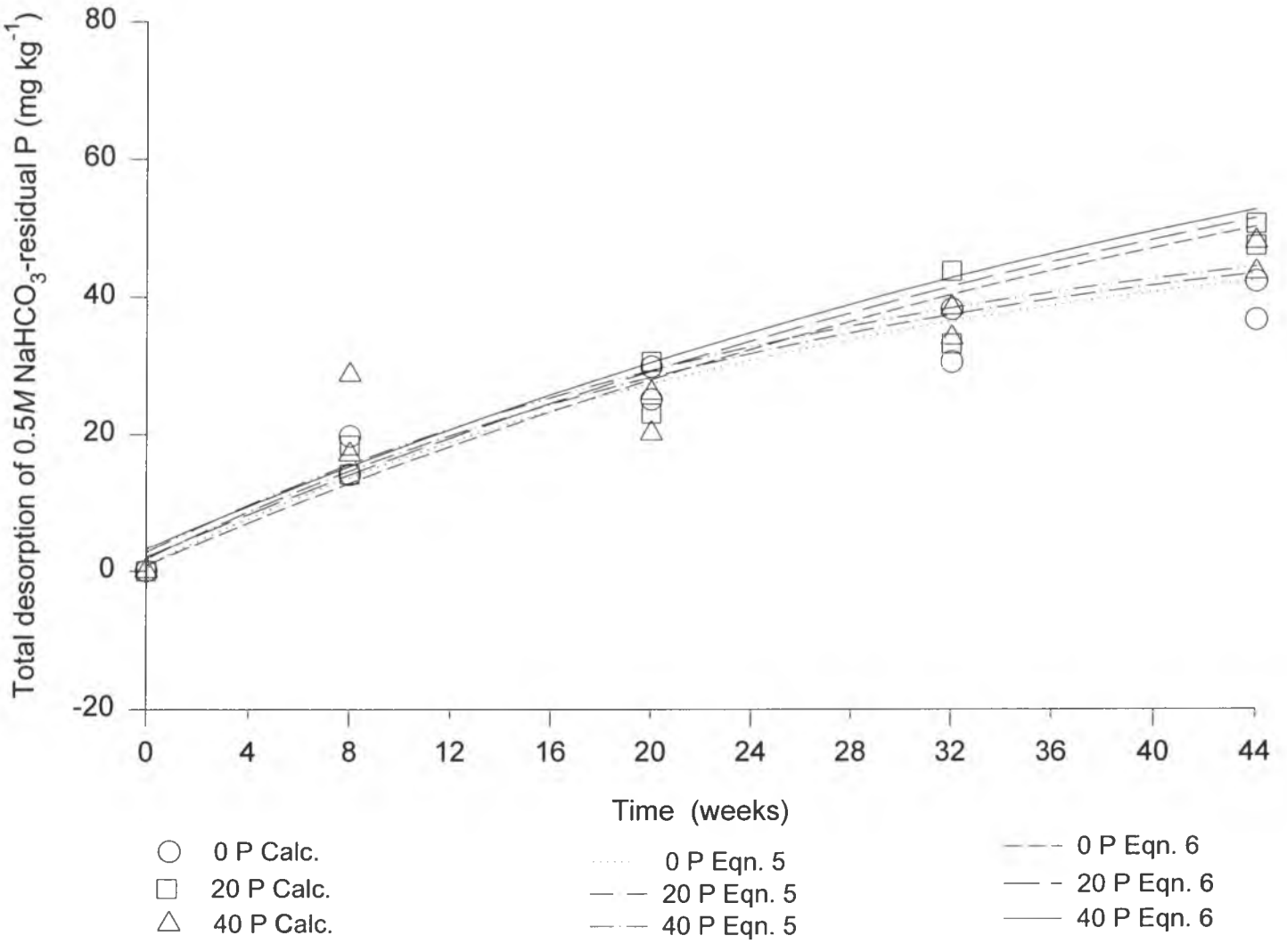


Figure 44. Calculated and predicted total desorption of 0.5*M* $NaHCO_3$-residual P of Serang soil.

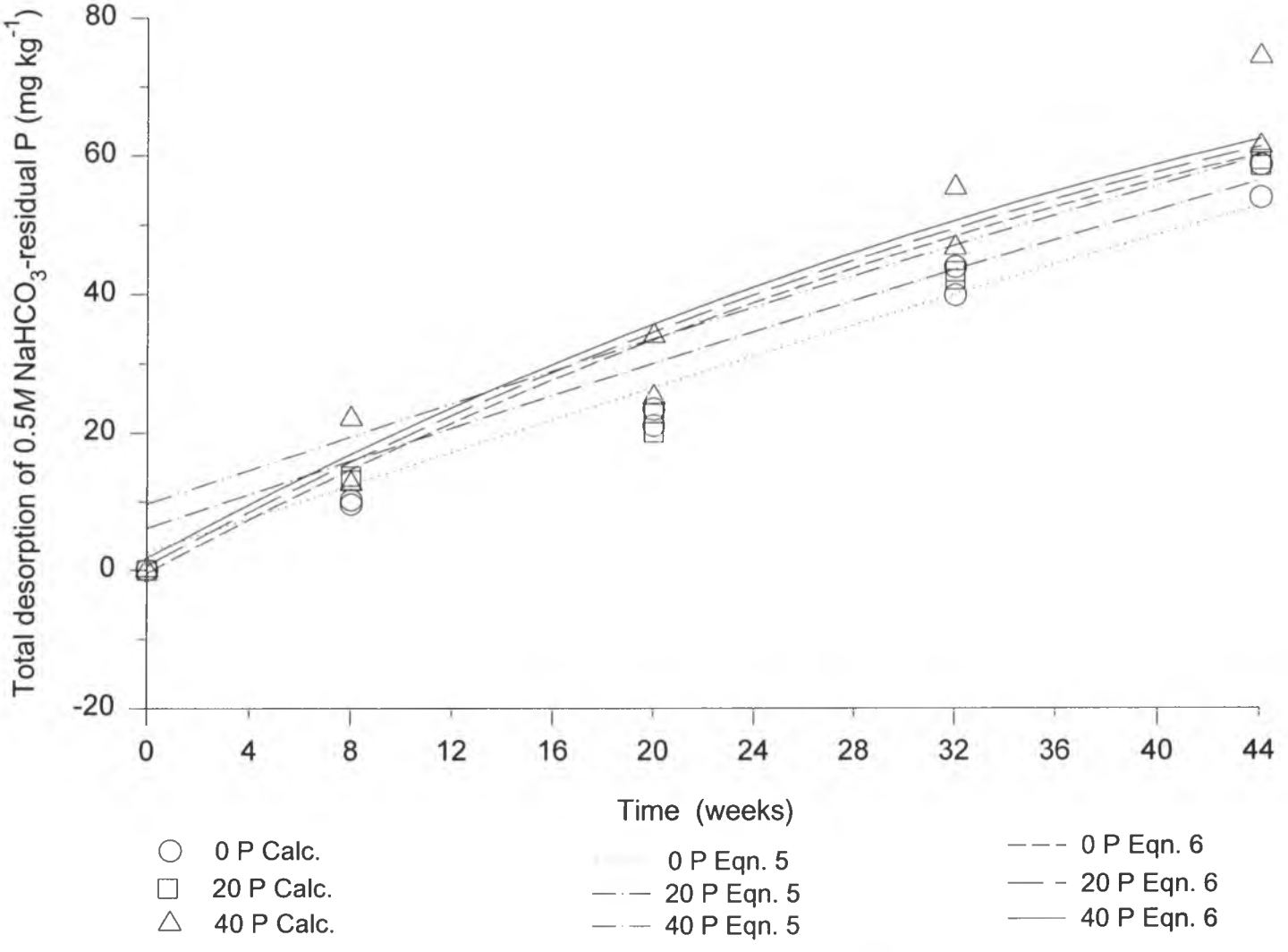


Figure 45. Calculated and predicted total desorption of 0.5*M* $NaHCO_3$-residual P of Kerawang soil.

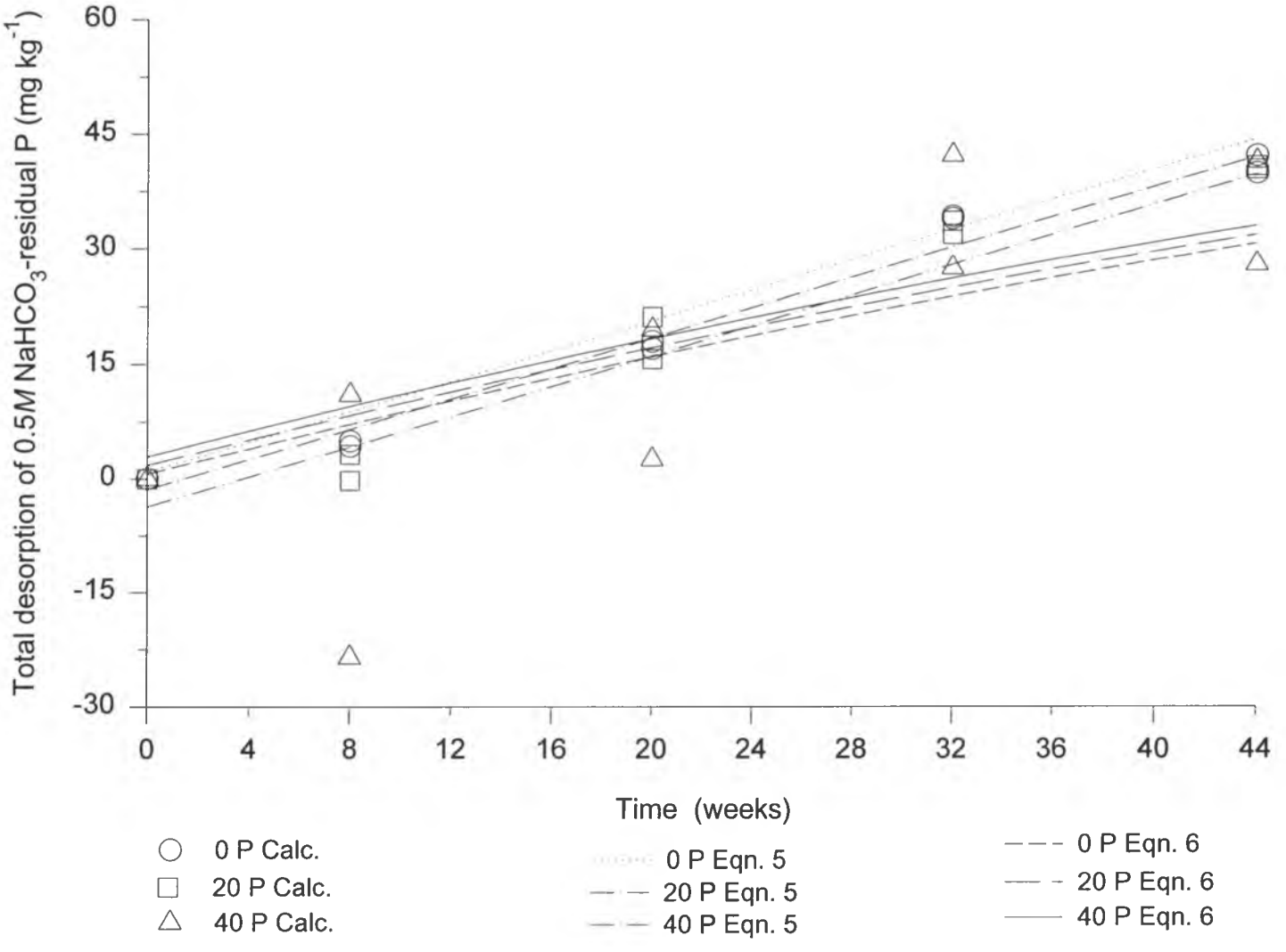


Figure 46. Calculated and predicted total desorption of 0.5*M* $NaHCO_3$-residual P of Brebes soil.

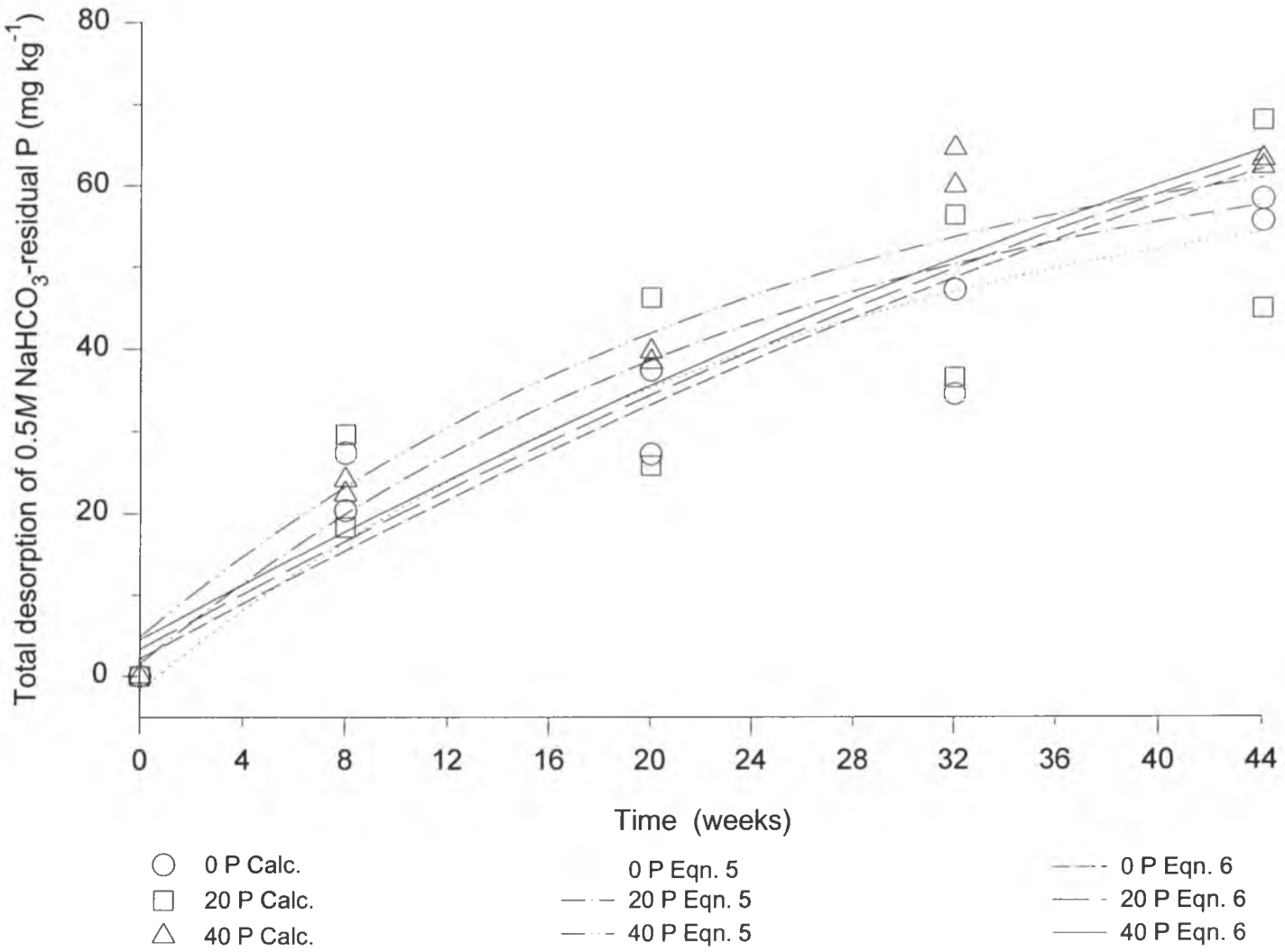


Figure 47. Calculated and predicted total desorption of 0.5*M* $NaHCO_3$-residual P of Silo soil.

4. 5. 1. 2. Total Desorption of HCl-residual P (TD of HCl-P)

Similar to total desorption of 0.5*M* $NaHCO_3$-residual P, the total desorption of HCl residual P was calculated using equation [4] of the Materials and Methods. The coefficients of correlation between total desorption of HCl residual P and some physical and chemical soil properties of soil representatives are listed in Table 22.

Table 22. Coefficient correlation between total desorption of HCl-residual P with some soil properties.

Soil Properties	Correlation Coefficient of total desorption of HCl-residual P:
pH	-0.151**
Clay content	-0.177**
15 bar %moisture	-0.049ns
Plasticity Index	-0.082ns
Clay physical activity	0.226**
Soil surface area	-0.031ns
Clay surface area	-0.227**
Organic carbon	0.163**
Calcium carbonate	-0.282**
Ammonium Oxalate Fe	-0.006ns
Ammonium Oxalate Al	-0.013ns
Initial 25% HCl extractable P	-0.220**

The degrees of freedom = 298; the r(298; 0.01) = 0.148; r(298; 0.05) = 0.113
ns) Non significant; *) significant; and **) highly significant.

The coefficients of linear correlation showed that soil pH (PH), clay content (CLAY), clay physical activity (CAT), clay surface area (CA), soil organic carbon (OC), and calcium carbonate content ($CaCO_3$) had a significant correlation with total

desorption of HCl-residual P. Therefore, all of these variables were then considered in process of selecting the best model to predict the total desorption of HCl-residual P.

The results of fitting the empirical model for predicting total desorption of HCl-residual P, equation [5], are presented in Table 23. Whereas the results of fitting the site specific model, equation [6] are shown in Table 24. There are also two models listed in Table 24, models 1f and 2f. Both models use similar soil variables. Model 1f, however, had better characteristics as a prediction model. First, because it had a smaller residual standard error, by 0.012 compare to model 2f. Second, because it had more parameters with significant coefficients than model 2f. Third, because model 1f employed clay content (CLAY) for the interaction term with P rather than clay physical activity (CAT). Clay content is easier to measure than clay physical activity. Therefore, model 1f was chosen as a preferred model for predicting the total desorption of HCl-residual P.

The preferred model included four soil variables, initial HCl-extractable P (EP_i), calcium carbonate content ($CaCO_3$), clay content (CLAY), and clay physical activity (CAT). Clay physical activity and calcium carbonate content performed an important role in the nonlinear portion of the model, whereas the calcium carbonate and clay content were important in the linear part of the model.

Table 23. Parameters resulting from fitting the empirical model (equation [5]) to total desorption of HCl-residual P.

Soil/Location	b0	b1	b2	k	RSE†
Serang	8.00	-0.0451	-0.975	-0.0418	13.3
Cianjur	-48.2	-0.126	42.3	-0.0119	36.9
Kerawang	6.35	-0.0242	-7.90	0.0954	15.4
Brebes	17.0	0.0451	-22.1	0.0813	17.2
Purbalingga	12.5	-0.0932	-12.0	0.127	20.0
Purwodadi	f.c.	f.c.	f.c.	f.c.	f.c.
Madiun	f.c.	f.c.	f.c.	f.c.	f.c.
Mojokerto	8.13	-0.131	-9.00	0.104	19.3
Silo	-9.44	0.727	-13.6	0.0519	28.4
Jenggawah	47.2	-0.141	-49.1	0.0544	17.4

†) Residual Standard Error of the model.
Equations were estimated from 30 observations. The t(26; 0.05) = 2.056; t(26; 0.01) = 2.779.
The model of equation [5] is: $EP_t = b0 + b1\ P + b2\ Exp(k\ Time)$.
f.c. = failed to converge.

Table 24. Parameters resulting from fitting the site specific model (equation [6]) to total desorption of HCl-residual P.

Model 1f‡	Parameters of Soil variables							
	a EP_i	C_v	b $CaCO_3$	c CLAY P	d $CaCO_3$ $e^{\{...\}}$	k0	k1 CAT	RSE†
Coefficient:	0.0153	4.7336	161.3313	-0.0009	-160.9744	0.1525	-0.2816	27.6858
t-value:	0.9880^{ns}	0.8851^{ns}	2.5501^{*}	-0.5308^{ns}	-2.5462^{*}	1.0284^{ns}	-1.0248^{ns}	
Equation:	$TD_t = (0.0153\ EP_i - 4.7336) + (161.3313\ CaCO_3) + (-0.0009\ \text{Clay P}) + \{-160.9744\ CaCO_3\ e^{\{(0.1525-0.2816\ CAT)\ Time\}}\}$							
Model 2f	a EP_i	C_v	b $CaCO_3$	c CAT P	d $CaCO_3$ $e^{\{...\}}$	k0	k1 CAT	RSE†
Coefficient:	0.0146	5.7925	159.9341	0.0274	-159.5848	0.1550	-0.2861	27.6973
t-value:	0.9548^{ns}	1.0232^{ns}	1.9486^{ns}	0.1951^{ns}	-1.9450^{ns}	1.0604^{ns}	-1.0563^{ns}	
Equation:	$TD_t = (0.0146\ EP_i - 5.7925) + (159.9341\ CaCO_3) + (0.0274\ \text{CAT P}) + \{-159.5848\ CaCO_3\ e^{\{(0.1550-0.2861\ CAT)\ Time\}}\}$							

Equations were estimated from 300 observations. The t(293; 0.05) = 1.960; t(293; 0.01) = 2.576.

†) Residual Standard Error of the model.

‡) Selected as the prediction model and for the final plot.

ns) = non significant; *) = significant; **) = highly significant.

The graphical presentation of the prediction model 1f, along with the empirical model (equation [5]) for all representative soils showed that for some soils HCl-residual P desorbed relatively fast until the end of second crop then desorption slowed gradually, see Figures 48 to 51 (also Figures 98 to 103 in the Appendix G). In general, model 1f revealed that the higher the clay physical activity the more rapid the total desorption of HCl-residual P of the soils (note: *due to the negative sign in front of the whole nonlinear term*). The net effect of calcium carbonate content might be insignificant to the total desorption of HCl-residual P. While, the higher the clay content of the soil the less rapid the total desorption of HCl-residual P.

Unlike the total desorption of $0.5M$ $NaHCO_3$-residual P, the total desorption of HCl-residual P was scattered and the model did not fit the data very well. Actually, for Purwodadi and Madiun soils even the empirical model fit poorly (Table 23).

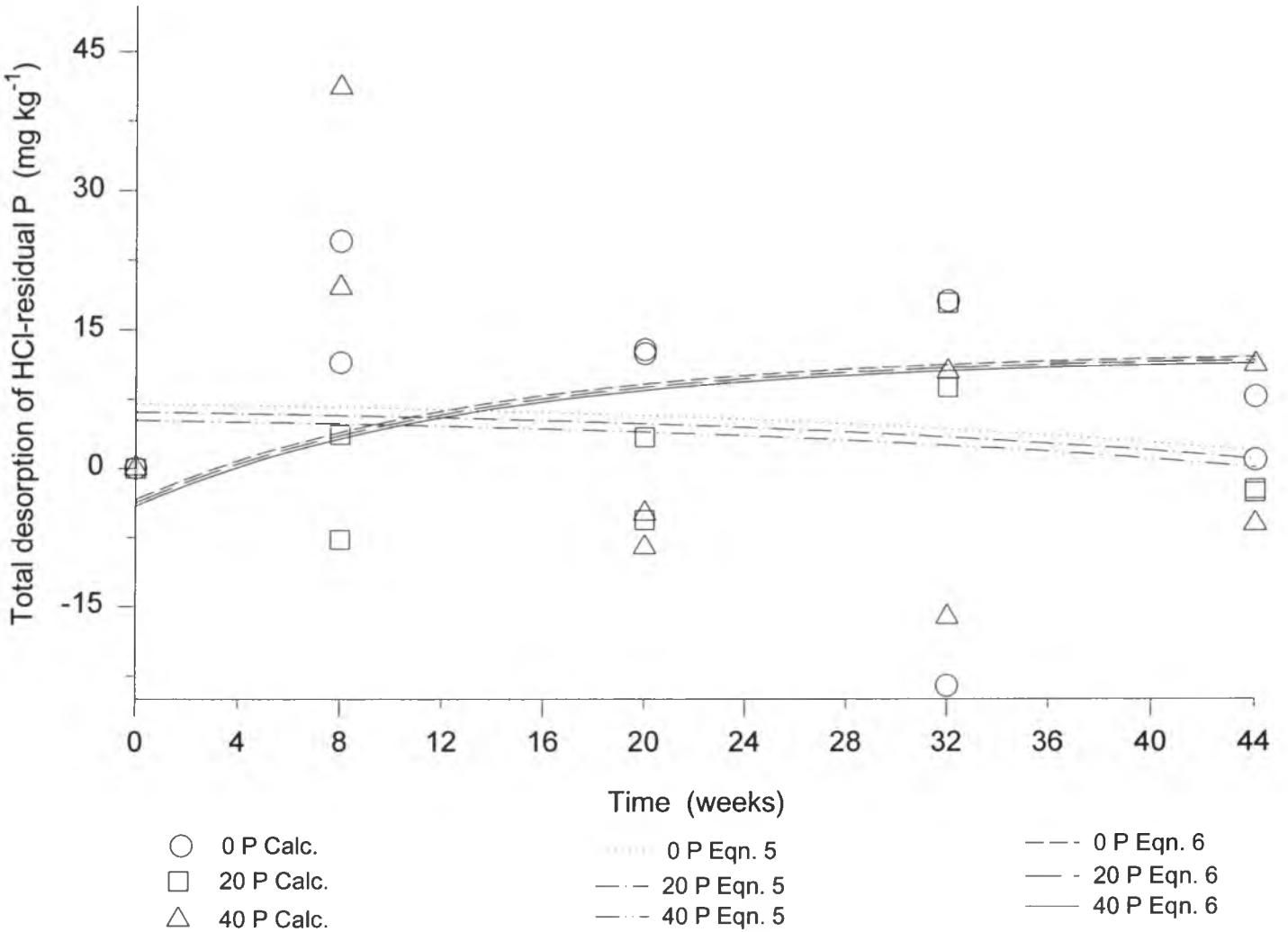


Figure 48. Calculated and predicted total desorption of HCl-residual P of Serang soil.

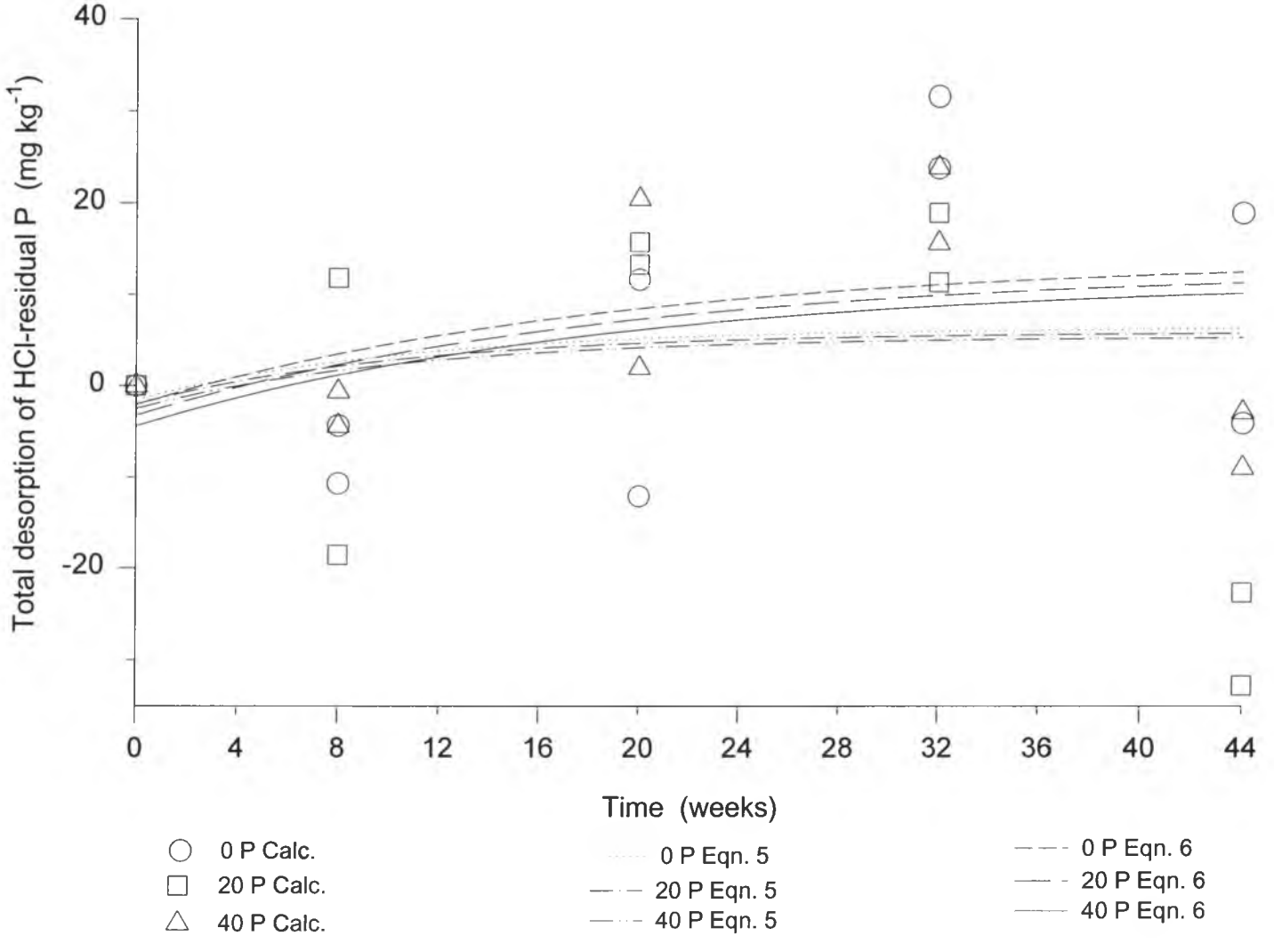


Figure 49. Calculated and predicted total desorption of HCl-residual P of Kerawang soil.

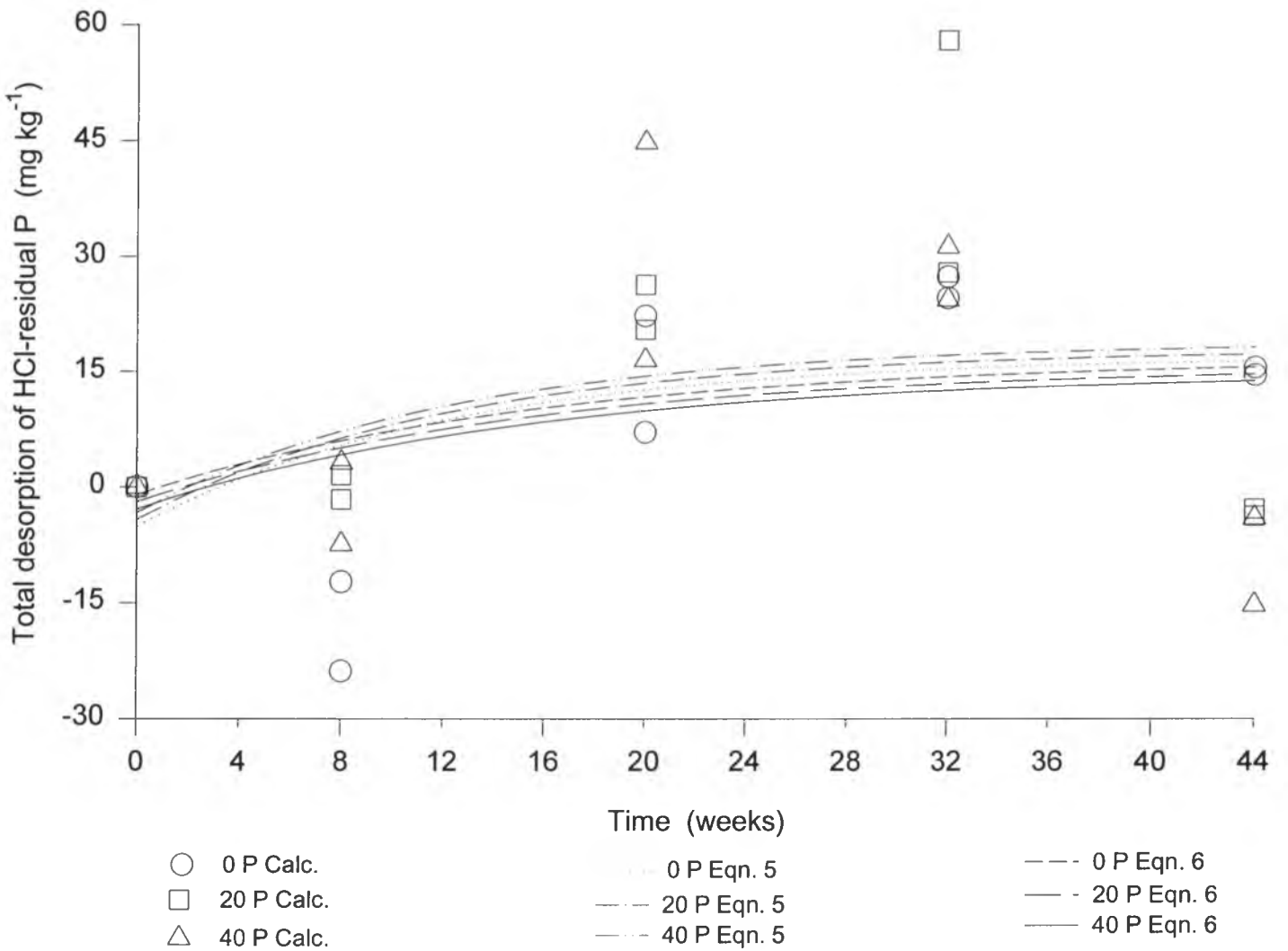


Figure 50. Calculated and predicted total desorption of HCl-residual P of Brebes soil.

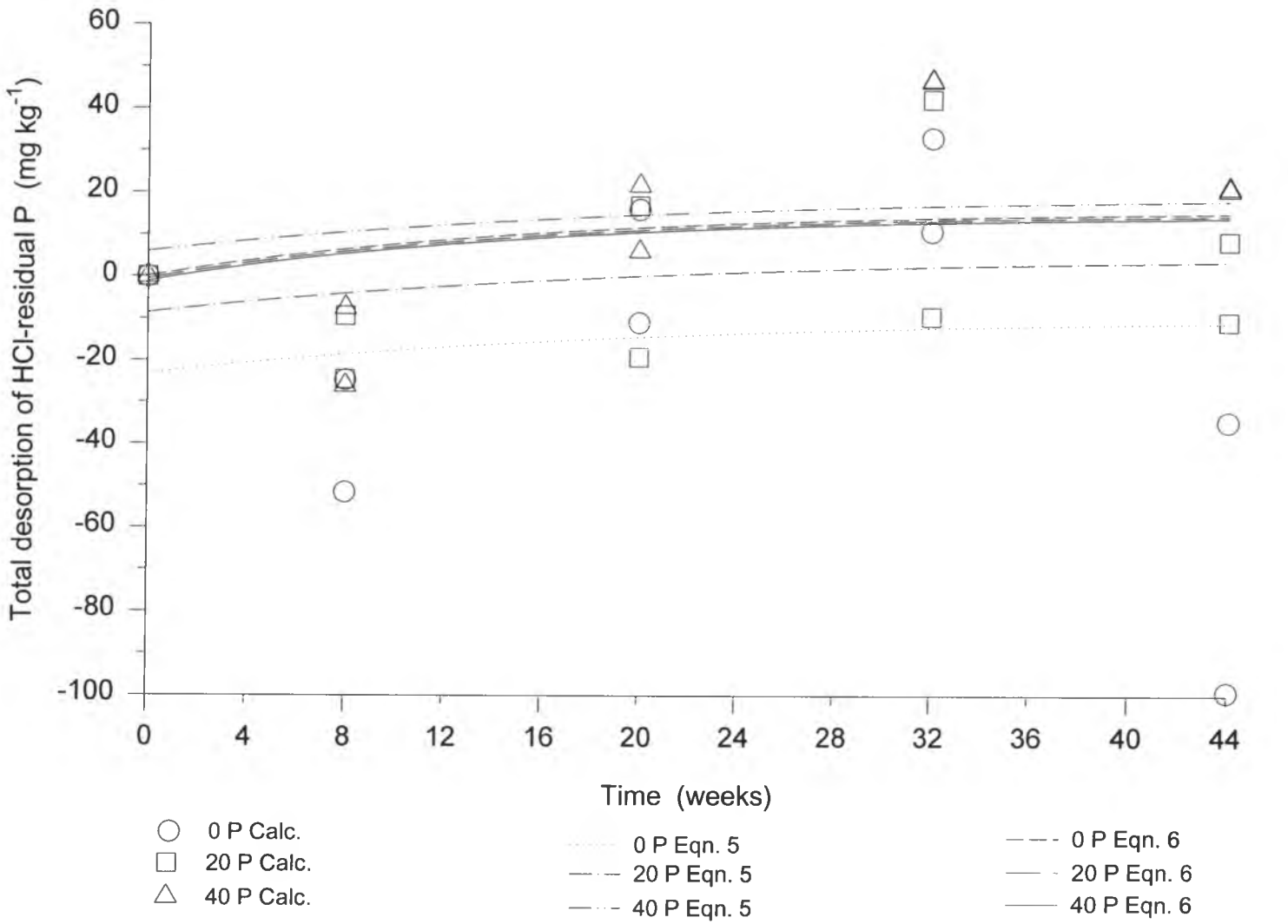


Figure 51. Calculated and predicted total desorption of HCl-residual P of Silo soil.

4. 5. 2. Net Desorption (ND)

The net desorption (ND) of residual P was defined as the difference between the desorption (F3) and adsorption (F2) (Figure 7) occurring at each crop, and is calculated using equation [10] of Chapter 3:

$ND_t = d(EP)_t + (CUP)_t - bc\ FP_t$ [equation 10 of Chapter 3],

where $d(EP)_t$ is the change in extractable P from planting to harvest time at any crop, t, CUP_t (F1 in Figure 7) is the plant P uptake at crop t, FP_t (F0 in Figure 7) is the amount of P fertilizer applied, and bc is the buffer coefficient of the soil.

4. 5. 2. 1. Net Desorption of 0.5*M* $NaHCO_3$-P
(ND of 0.5*M* $NaHCO_3$-P)

The correlations between net desorption of 0.5*M* $NaHCO_3$-residual P with some physical and chemical soil properties of representative soils are listed in Table 25.

Table 25. Coefficients of correlation of net desorption (ND_t) of 0.5*M* $NaHCO_3$-residual P with soil properties.

Soil Properties	Correlation Coefficient of net desorption of 0.5*M* $NaHCO_3$-residual P:
pH	-0.192**
Clay content	-0.022ns
15 bar %moisture content	-0.061ns
Clay physical activity	0.218**
Soil surface area	0.083ns
Clay surface area	-0.096ns
Organic carbon	0.168*
Calcium Carbonate	-0.145*
Ammonium Oxalate Fe	0.075ns
Ammonium Oxalate Al	-0.006ns
Initial 0.5*M* $NaHCO_3$-extractable P	-0.144*

The degree of freedom = 238; the r(238; 0.01) = 0.169; r(238; 0.05) = 0.129
ns) Non significant; *) significant; and **) highly significant.

The correlation coefficient showed that soil pH (PH), clay physical activity (CAT), organic carbon content (OC), calcium carbonate content ($CaCO_3$), and initial 0.5*M* $NaHCO_3$-extractable P (OLSENPI) were significantly related to ND_t of 0.5*M* $NaHCO_3$-P. Therefore, all of these variables were considered in the developing model for predicting the net desorption of 0.5*M* $NaHCO_3$-residual P. The results of fitting the site specific model of equation [12] to the calculated net desorption of 0.5*M* $NaHCO_3$-residual P are presented in Table 26.

Table 26. Parameters resulting from site specific model of equation [12] to net desorption of 0.5*M* $NaHCO_3$-residual P.

Model 1g‡	Parameters of Soil variables				
	a CAT	b OLSENPI P	c OC $exp^{\{-(...)Time\}}$	k1 PH Time	RSE†
Coefficient:	17.998	-0.00315	163.518	0.0659	5.7745
t-value:	22.197**	-3.361**	2.950**	7.889**	
Equation:	$ND_t = (17.998\ CAT) + (-0.00315\ OLSENPI\ P) + [163.518\ OC\ exp^{\{-(0.0659\ PH)\ Time\}}]$				
Model 2g	a CAT	b OLSENPI P	c PH $exp^{\{-(...)Time.\}}$	k1 PH Time	RSE†
Coefficient:	18.106	-0.00344	97.677	0.0794	5.9450
t-value:	21.907**	-3.570**	2.806**	9.060**	
Equation:	$ND_t = (18.106\ CAT) + (-0.00344\ OLSENPI\ P) + [97.677\ PH\ exp^{\{-(0.0794\ PH)\ Time\}}]$				

Equations were estimated from 240 observations. The t(236; 0.05) = 1.960; t(236; 0.01) = 2.576.

†) Residual Standard Error of the model.

‡) Selected as the prediction model and for the final plot.

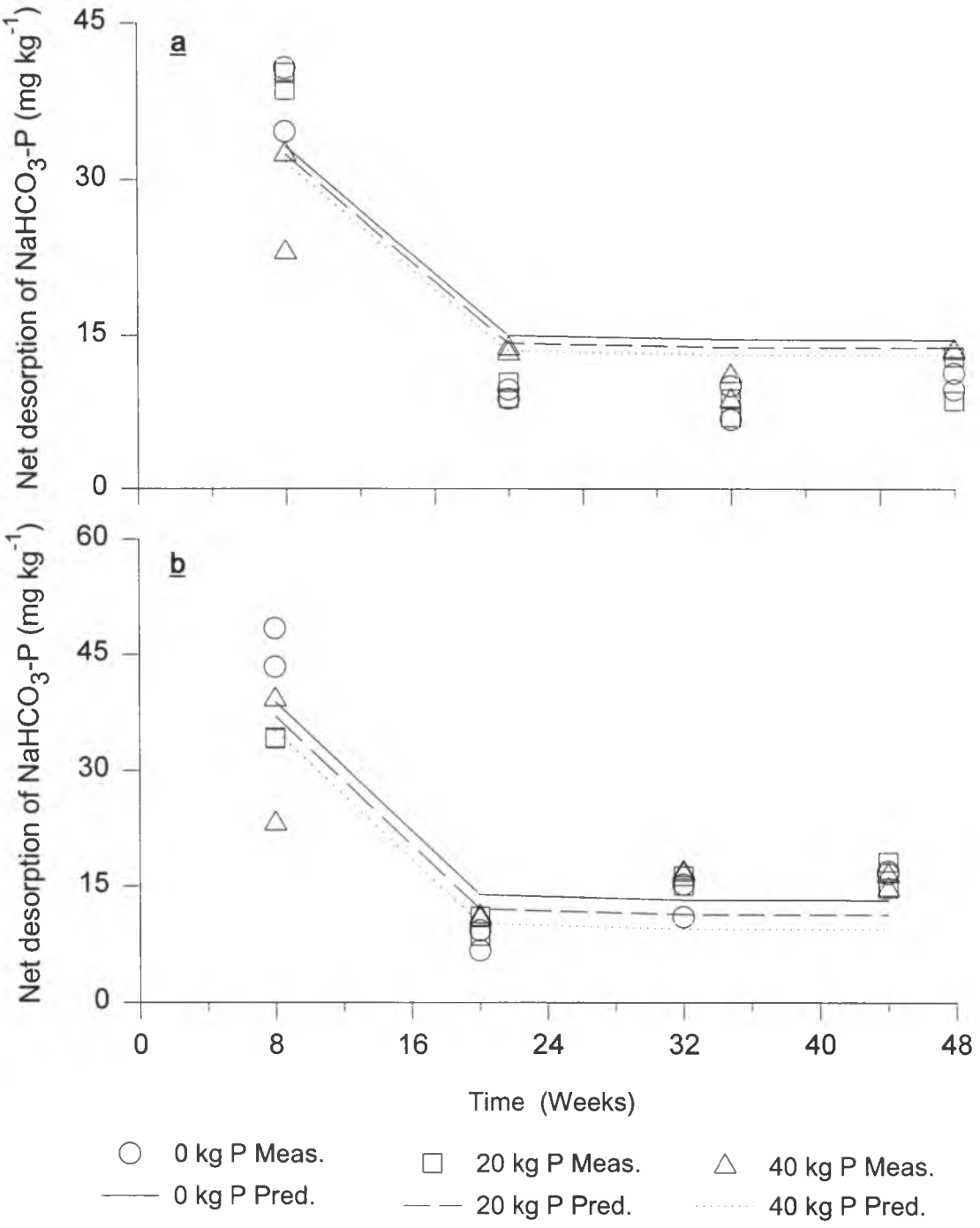
ns) = non significant; *) = significant; **) = highly significant.

Two models, 1g and 2g, are listed in Table 26. Both models use similar soil variables. Soil acidity was important in the nonlinear part of both models. Model 1g had one extra variable, OC, however, it had a smaller residual standard error than model 2g. Therefore, model 1g was selected as a preferred model for predicting the net desorption of 0.5*M* $NaHCO_3$-P.

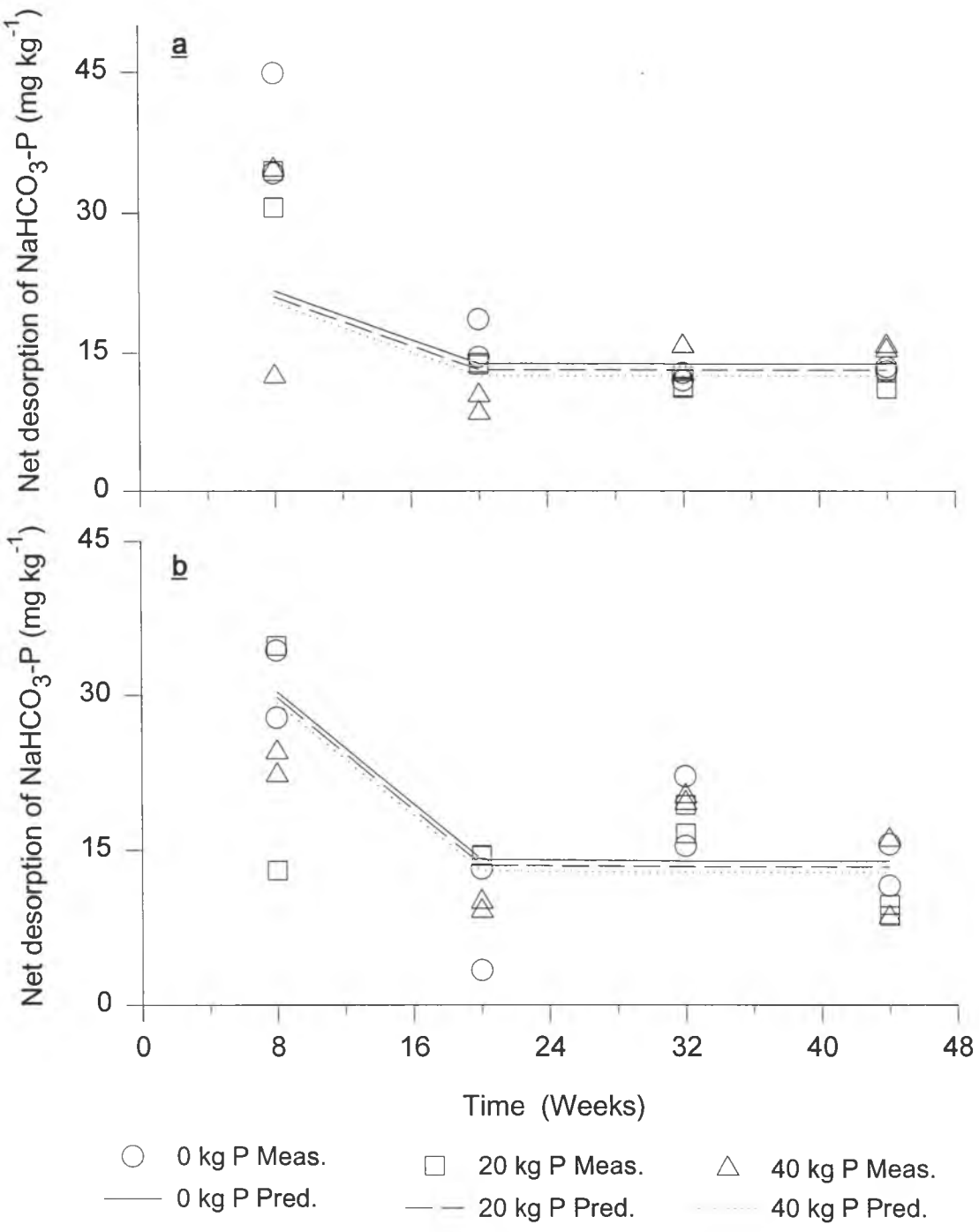
The preferred model involved four soil variables, clay physical activity, initial 0.5*M* $NaHCO_3$-extractable P, organic carbon content, and soil acidity. Soil pH affected the nonlinear part of the model. The higher the soil pH the smaller the net desorption of the soil. This might be true since the higher the pH of the soil the more P is being held by Ca and precipitated as Ca-phosphate compounds (Parfitt, 1978; Smillie *et al.*, 1987; Naidu *et al.*, 1990). Clay physical activity and initial 0.5*M* $NaHCO_3$-extractable P affected the linear part of the model. Clay physical activity and organic carbon positively influenced the net desorption of 0.5*M* $NaHCO_3$-P, and initial 0.5*M* $NaHCO_3$-extractable P negatively influenced the net desorption of 0.5*M* $NaHCO_3$-residual P. These results concur with significant correlation of those variables (clay physical activity, organic carbon, soil pH, and initial 0.5*M* $NaHCO_3$-extractable P) with the net desorption of 0.5*M* $NaHCO_3$-residual P.

The graphical presentation of the prediction model 1g along with the calculated ND of 0.5*M* $NaHCO_3$-P for all representative soils showed that the net desorption of 0.5*M* $NaHCO_3$-residual P decreased very rapidly at the first crop, then reached a constant flow thereafter, see Figures 52a & b to 53a & b (also Figures 104a

& b to 106a & b in the Appendix H). The rapid decrease in net desorption from the first crop to the second crop was most likely caused by two factors. They were: a) the fast decrease of extractable P which occurred during the first crop, and b) much higher P crop uptake of the first crop compared to the second, third, and fourth crops (Figures 19 a & b to 23 a & b).



Figures 52a & b. Calculated and predicted net desorption of $NaHCO_3$-P of Serang (a), and Kerawang (b) soils.



Figures 53a & b. Calculated and predicted net desorption of $NaHCO_3$-P of Brebes (a), and Silo (b) soils.

4. 5. 2. 2. Net Desorption of HCl-residual P (ND HCl-P)

The coefficients of linear correlation between net desorption of HCl-residual P with soil properties of all representative soils are listed in Table 27. Clay physical activity (CAT) and organic carbon (OC) were significantly related to net desorption of HCl-residual P. Because the initial HCl-extractable P (HCLPI) was very close to significance at the 5% level, therefore this soil variable together with clay physical activity and organic carbon were considered in the process of selecting the best site specific model (of equation [12]) for predicting net desorption of HCl-residual P.

Table 27. Coefficients of linear correlation of net desorption (ND) of HCl-residual P with soil properties.

Soil Properties	Correlation Coefficient of net desorption of HCl-residual P:
pH	-0.047^{ns}
Clay content	-0.051^{ns}
15 bar %Moisture content	-0.015^{ns}
Clay physical activity	0.211^{**}
Soil surface area	0.086^{ns}
Clay surface area	-0.042^{ns}
Organic carbon	0.141^{*}
Calcium Carbonate	-0.072^{ns}
Ammonium Oxalate Fe	-0.065^{ns}
Ammonium Oxalate Al	-0.093^{ns}
Initial HCl extractable P	-0.125^{ns}

Degrees of freedom = 238; r(238; 0.01) = 0.169; r(238; 0.05) = 0.129

^{ns}) Non significant; *) significant; and **) highly significant.

The results of fitting the site specific model of equation [12] to the calculated net desorption of HCl-residual P are presented in Table 28. Two models were listed in Table 28, model 1h and 2h. Both models use exactly the same soil variables, initial HCl-extractable P and organic carbon content. The organic carbon content was significant on the nonlinear portion of the model, while the initial HCl-extractable P was influential on the linear part of the model. The model 1h had a smaller residual standard error than model 2h by 1.09. Model 1h, however, did not include the interaction term with the amount of P fertilizer applied which supposed to have significant contribution in practical application. Therefore, the model 2h was selected to represent the model for predicting for net desorption of HCl-residual P.

The preferred model 2h showed that the higher the organic carbon content the lower the net desorption of HCl-residual P of the soil. Sanyal and De Datta (1991) suggested that organic carbon content in the soil could have both positive and negative correlation with phosphate sorption. The positive correlation between organic carbon content and phosphate sorption was attributed to organically bound Al and Fe, and there is some indication that organic complexes can sorb more P than can the same amount of free Fe and Al oxides (Sanyal and De Datta, 1991). The model 2h also showed that the higher either the initial HCl-extractable P and/or the amount of P fertilizer applied, the lower the net desorption of HCl-residual P.

Table 28. Parameters resulting from site specific model of equation [12] to net desorption of HCl-residual P.

Model 1h	Parameters of Soil variables				
	a HCLPI	Constant	b OC $exp^{\{-(...)Time\}}$	k1 OC Time	RSE†
Coefficient:	-0.0476	24.756	65.602	0.0121	41.8997
t-value:	-2.853**	2.267*	8.613**	5.617**	
Equation:	$ND_t = (-0.0476\ HCLPI - 24.756) + [65.602\ OC\ exp^{\{-(0.0121\ OC)\ Time\}}]$				
Model 2h‡	a HCLPI P	b OC $exp^{\{-(...)Time\}}$		k1 OC Time	RSE†
Coefficient:	-0.00117	46.321		0.0182	42.9854
t-value:	-2.710**	8.242**		5.077**	
Equation:	$ND_t = (-0.00117\ HCLPI\ P) + [46.321\ OC\ exp^{\{-(0.0182\ OC)\ Time\}}]$				

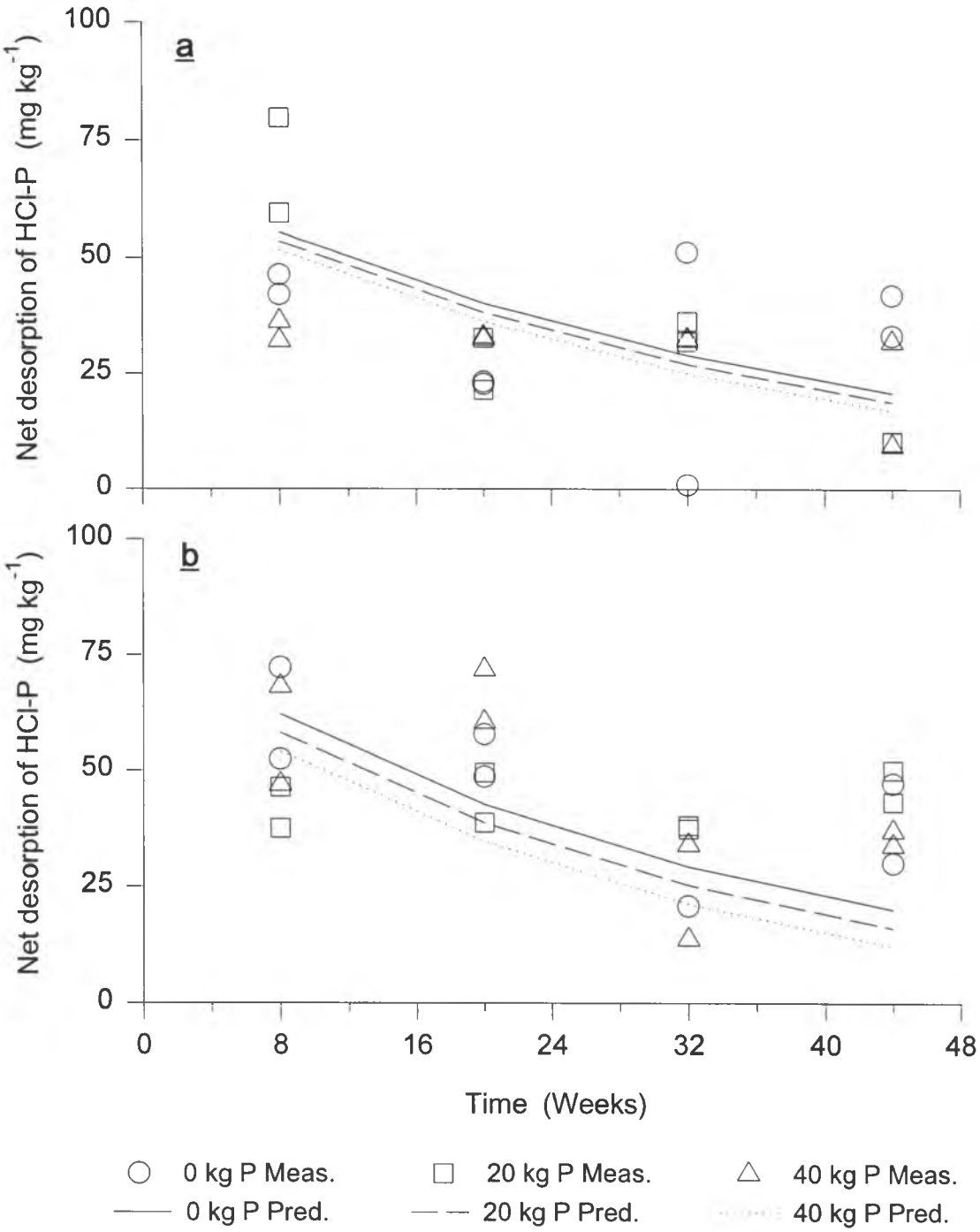
Equations were estimated from 240 observations. The t(236; 0.05) = 1.960; t(236; 0.01) = 2.576.

†) Residual Standard Error of the model.

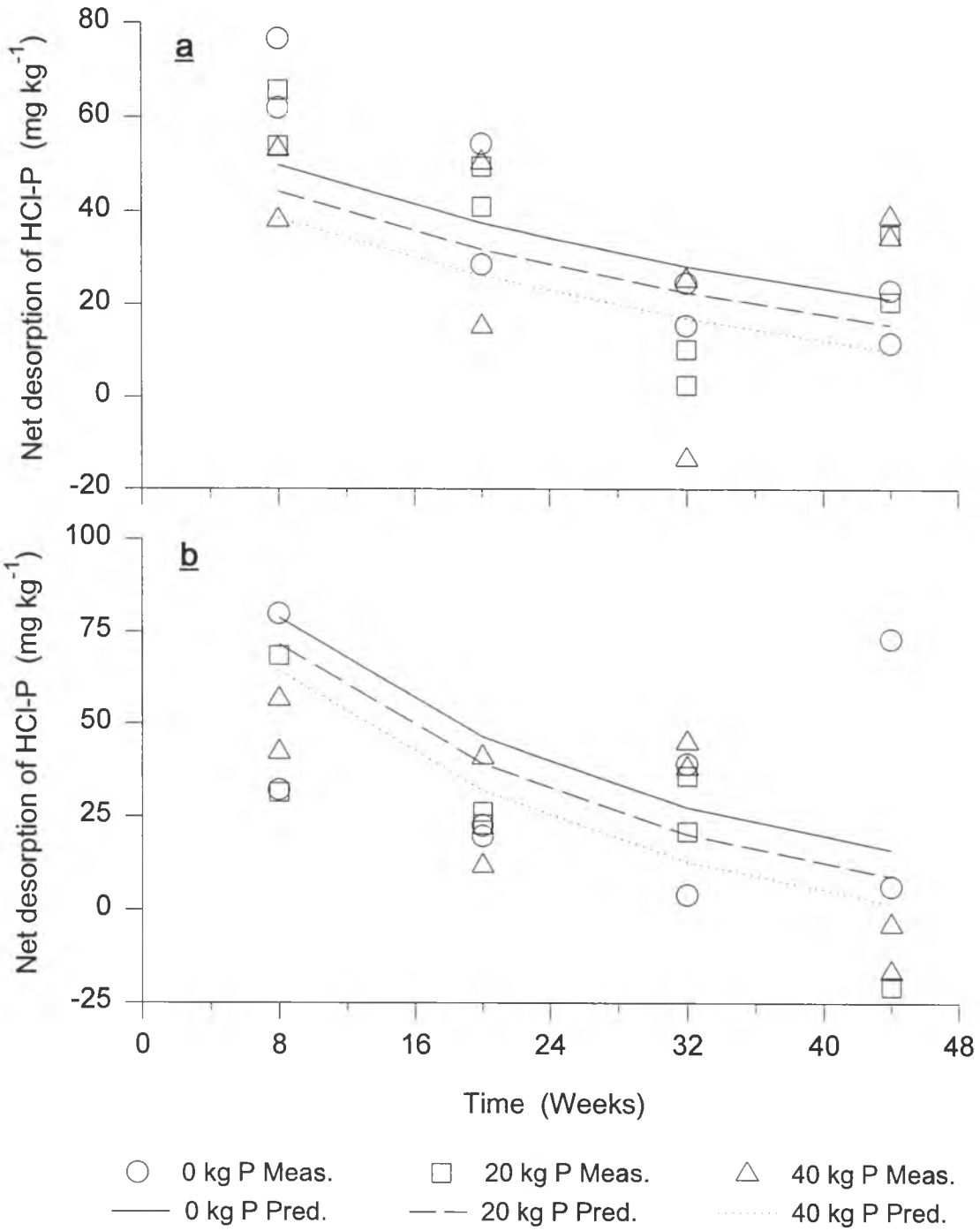
‡) Model selected for the final plot.

ns) = non significant; *) = significant; **) = highly significant.

In general, the graphical presentation of the preferred model 2h along with the calculated net desorption of HCl-residual P for all representative soils showed that the net desorption of HCl-residual P decreased in almost a constant rate but was relatively slower after the first crop, see Figures 54a & b to 55a & b (also Figures 107a & b to 109a & b). In some soils the value of net desorption of HCl-residual P was estimated as negative values indicating that adsorption of P from the extractable P pool to the residual P pool had occurred instead of desorption from the residual P pool to the extractable P pool.



Figures 54a & b. Calculated and predicted net desorption of HCl-P of Serang (a), and Kerawang (b) soils.



Figures 55a & b. Calculated and predicted net desorption of HCl-P of Brebes (a), and Silo (b) soils.

4. 6. Results Presentation using Geographical Information Systems

A geographical information system (GIS) combines mapping capabilities with analytical models and can be used to investigate the impacts of management practices on the environment. In this study, a GIS software, ARC/INFO® was used to perform mapping and analytical procedures. With soil units as the base map and using the soil database information attached to the soil units, an equation that predicts the residual extractable P was applied to produce a map representation of the predicted extractable P. Only those soils that have a complete soil database needed for the prediction were mapped.

Some assumptions in representing geographical data and/or the results of predicted values were necessary to map using a geographical information systems (GIS) software. Those assumptions were: 1) soil embodied within one polygon has homogenous physical and chemical soil properties throughout the polygon; 2) similarly, the selected model will apply to all other polygons having the same soil characteristics as the soils of the sampling sites.

For mapping purposes, both 0.5*M* $NaHCO_3$- and HCl-extractable P were classified into three categories based on availability for normal rice growth: low, medium, and high. These categories are used by the Centre for Soil and Agroclimate Research (CSAR) of Bogor, Indonesia. For 0.5*M* $NaHCO_3$-extractable P is considered low if it is less than the critical level for rice growth which is 4.4 mg kg^{-1} medium if the it falls between 4.4 and 10.9 mg kg^{-1}, and considered high if it is higher

than 10.9 mg kg^{-1} (Moersidi *et al.*, 1989; Nursyamsi *et al.*, 1993). HCl-extractable P categories are: low, if HCl-extractable P is less than the critical level, 87.3 mg kg^{-1}; medium, if it is between 87.3 to 175 mg kg^{-1}; and high if it is greater than 175 mg kg^{-1} (Santoso and Sudjadi, 1974; Moersidi *et al.*, 1989).

4. 6. 1. Mapping the Initial Extractable P

It is important to map the initial extractable P for all representative soils, so that the updated maps from the selected model for predicting extractable P could be evaluated. Initial extractable P of both methods, 0.5*M* $NaHCO_3$ and 25% HCl, were mapped separately. Figures 56 to 58 display the maps of initial 0.5*M* $NaHCO_3$-extractable P, while Figures 59 to 61 show the maps of initial HCl-extractable P for East Java, Central Java, and West Java, respectively.

Of the ten representative soils, two of them, Kerawang and Brebes soils, have the same soil classification category which is dark grey Alluvial soil. For mapping purposes, however, only one of them was used - Kerawang soil. That was the reason why the map for initial 0.5*M* $NaHCO_3$-extractable P for Brebes soil (sampling site no. 1) on Figure 57 was indicated as high (red color), while the actual value was medium (10. 5 mg P kg^{-1}). Likewise, if data of Brebes soil were used instead of Kerawang to represent that particular soil, the map of initial 0.5*M* $NaHCO_3$-extractable P of Kerawang soil would have been medium. This, however, did not cause any difference on the mapping of initial HCl-extractable P of both soils, since the initial HCl-extractable P for both soils was high.

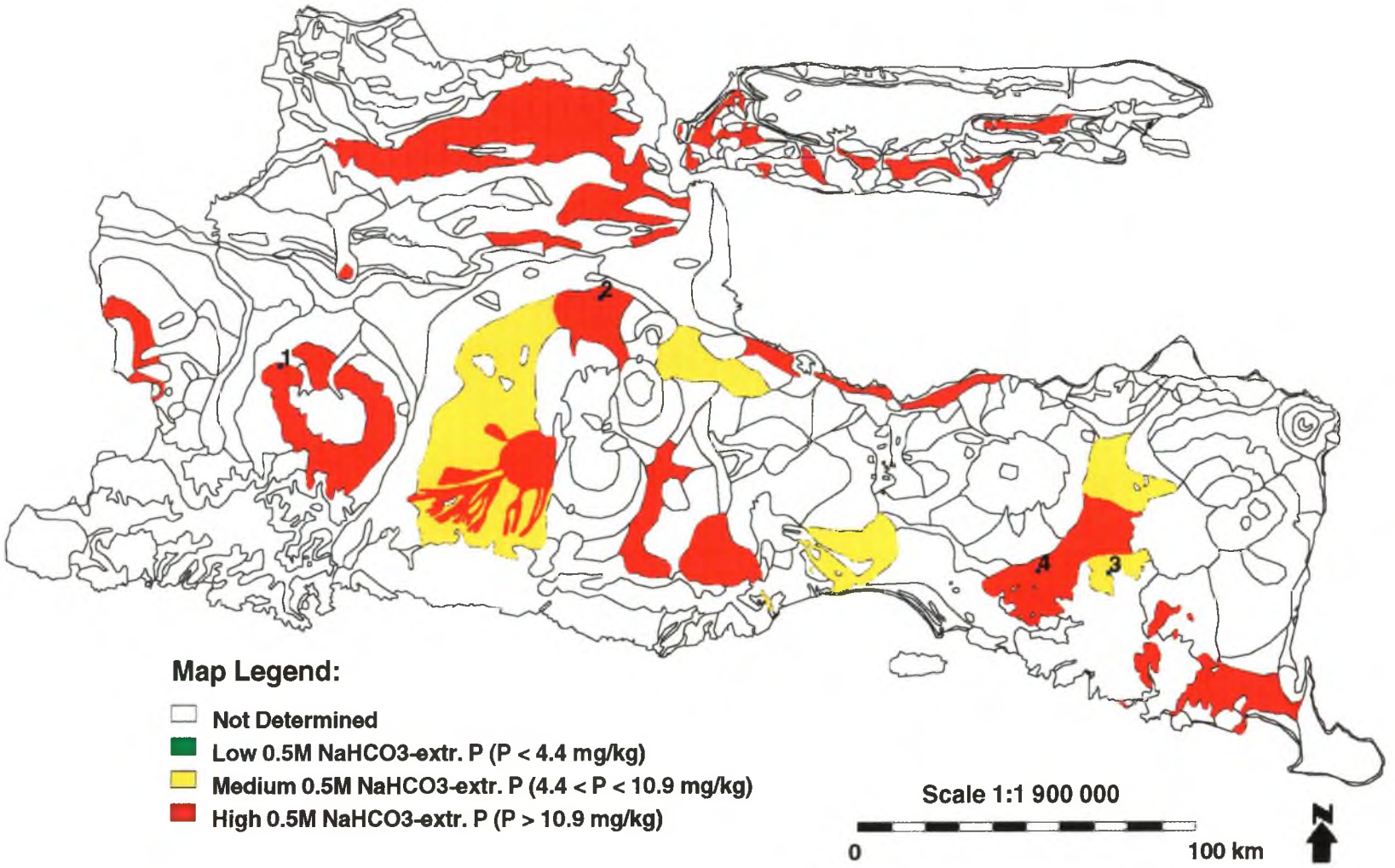


Figure 56. Map of initial 0.5*M* $NaHCO_3$-extractable P of East Java soils (111°20'–114°40' East Longitude and 6°40–8°45' South Latitude).

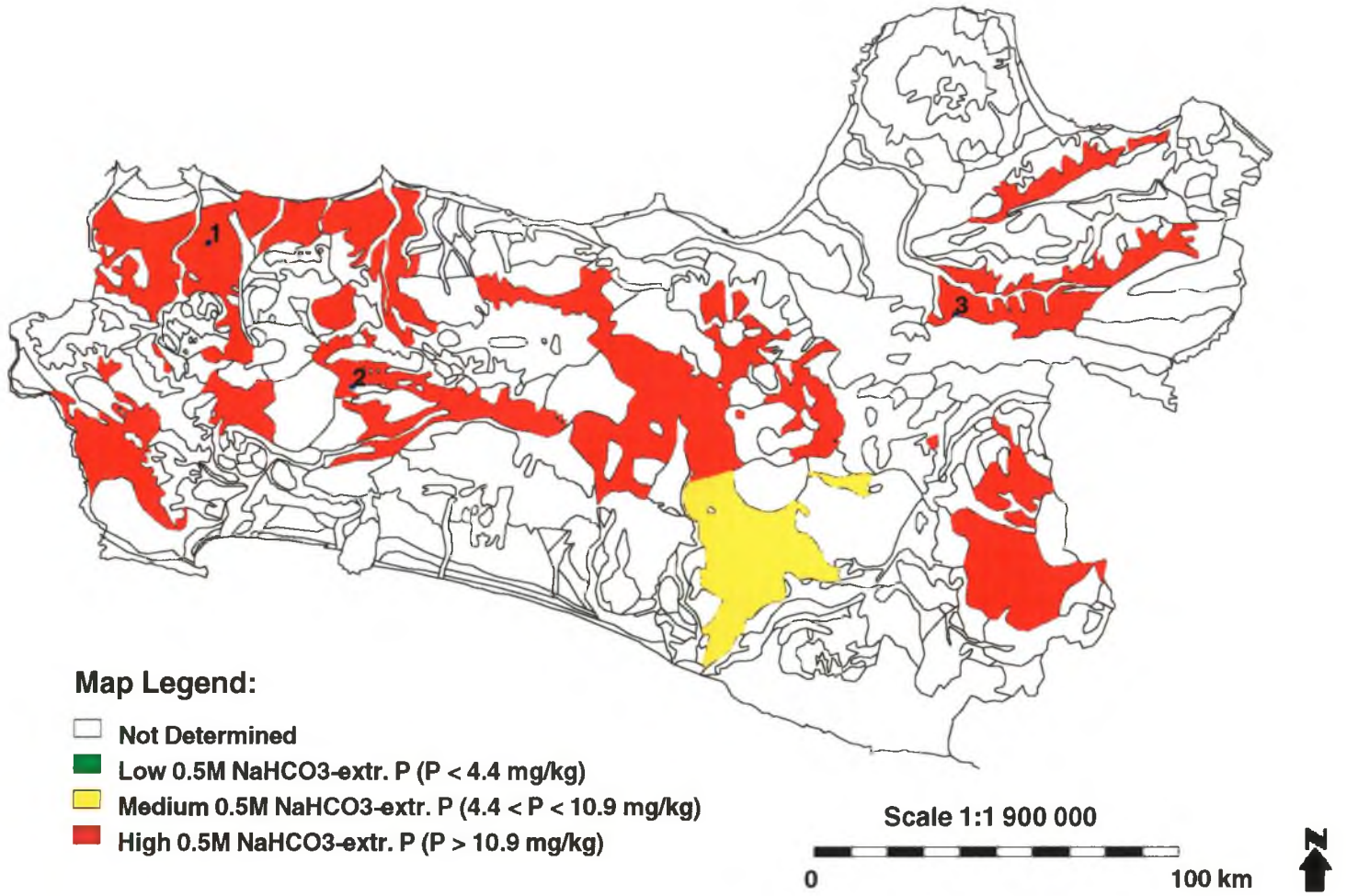


Figure 57. Map of initial 0.5*M* $NaHCO_3$-extractable P of Central Java soils (108°40'–111°40 East Longitude and 6°40'–8°20' South Latitude).

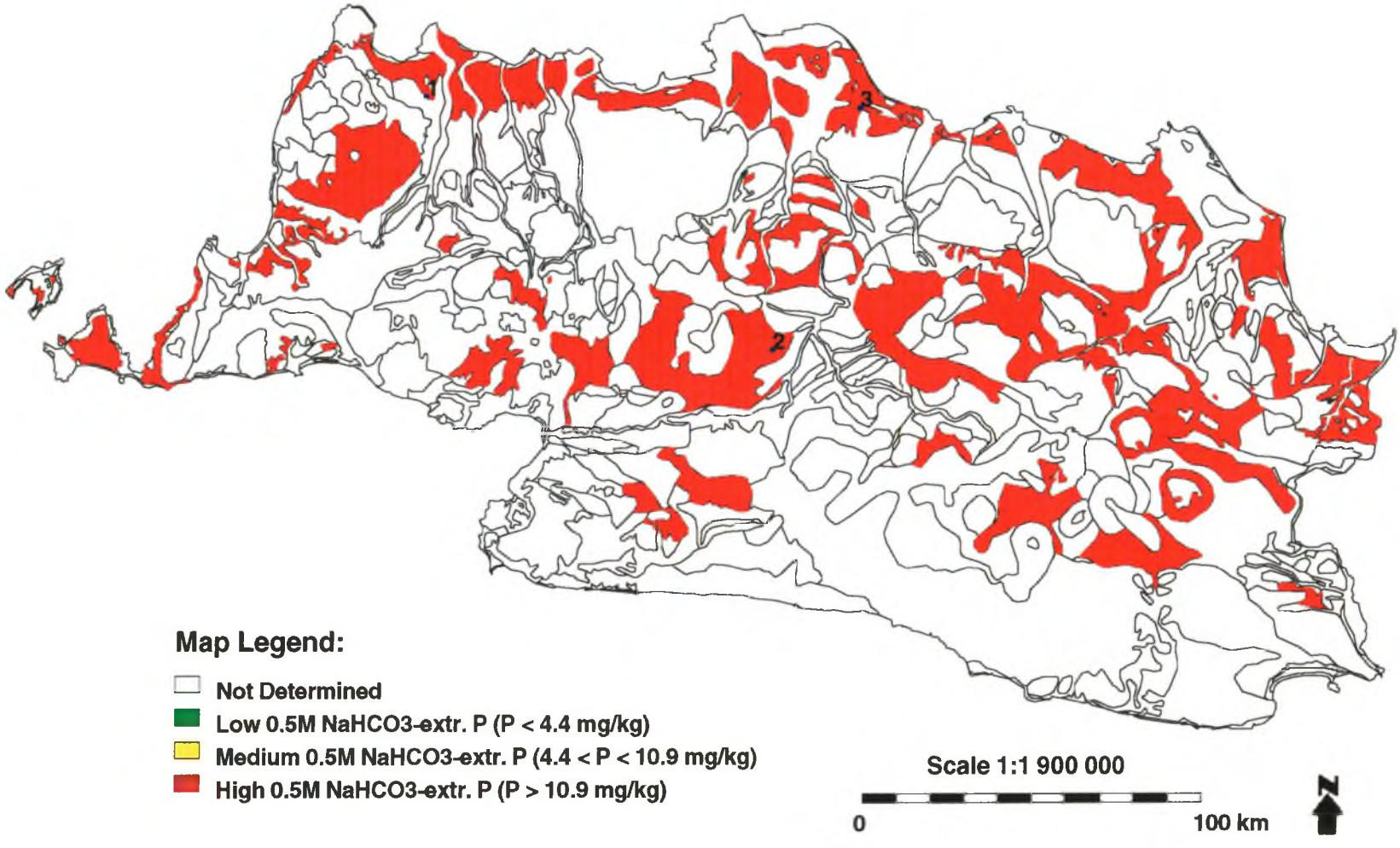


Figure 58. Map of initial 0.5*M* $NaHCO_3$-extractable P of West Java soils (105°–108°40' East Longitude and 6°–7°40' South Latitude).

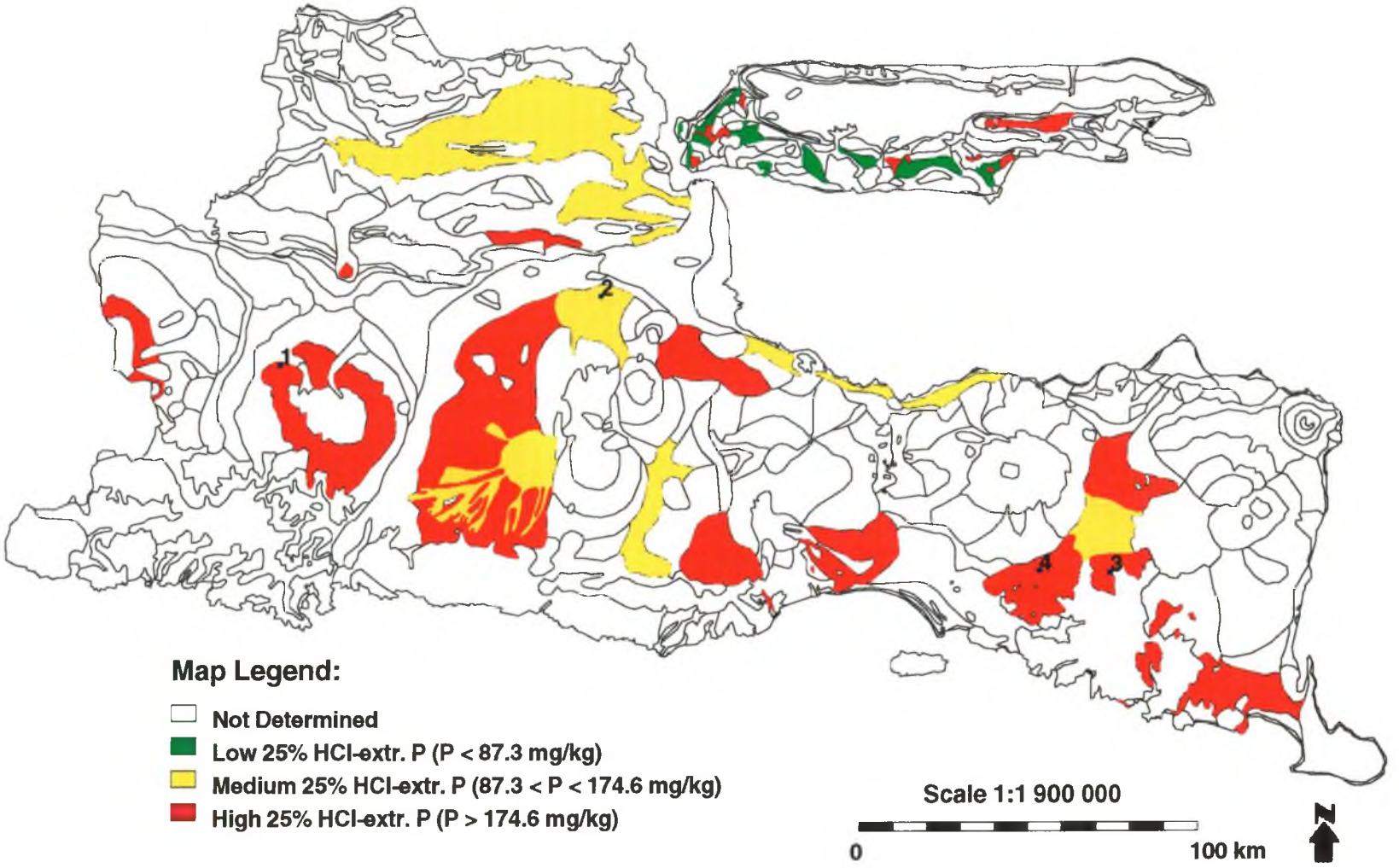


Figure 59. Map of initial HCl-extractable P of East Java soils (111°20'–114°40' East Longitude and 6°40–8°45' South Latitude).

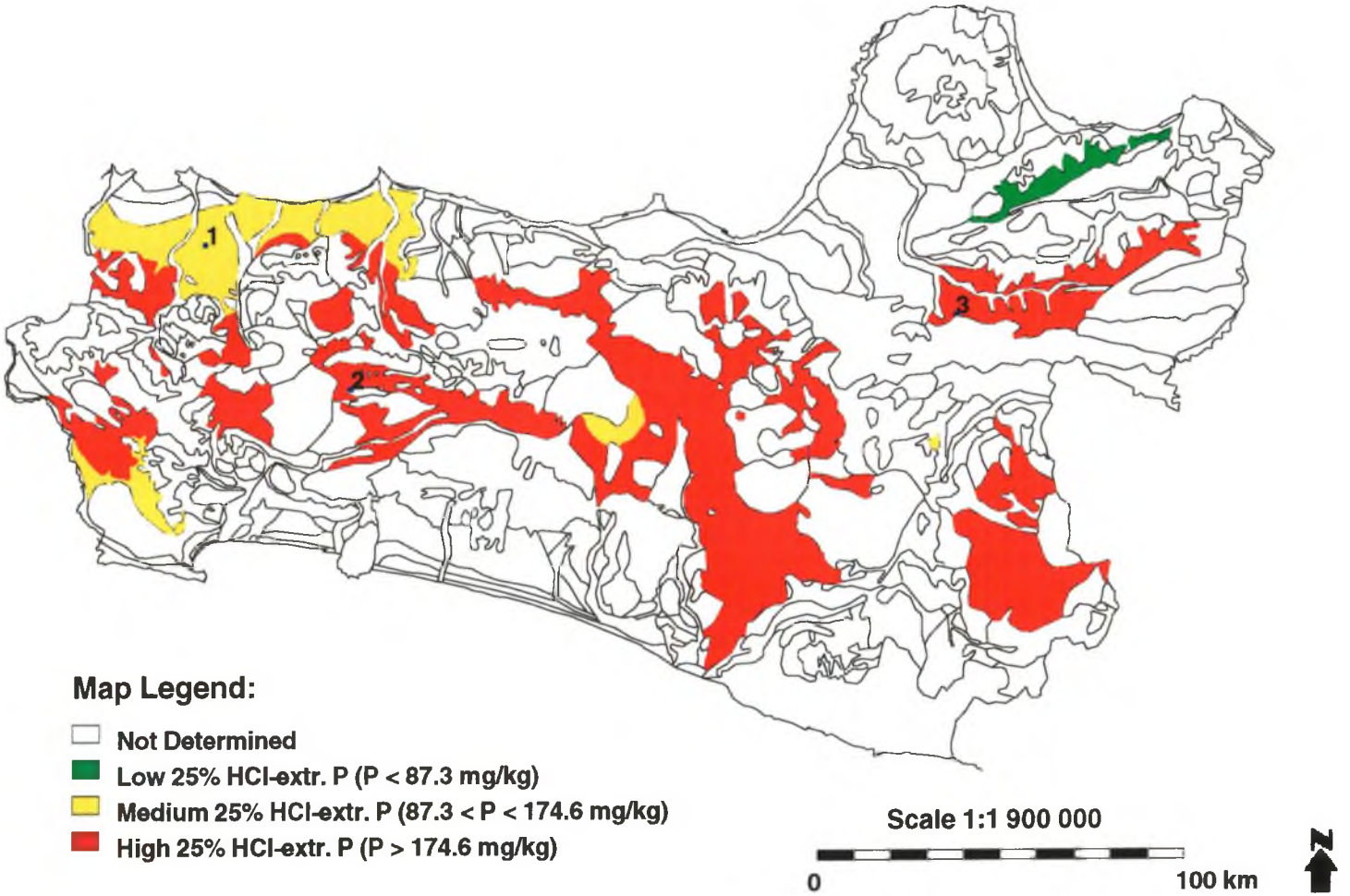


Figure 60. Map of initial HCl-extractable P of Central Java soils (108°40'–111°40 East Longitude and 6°40'–8°20' South Latitude).

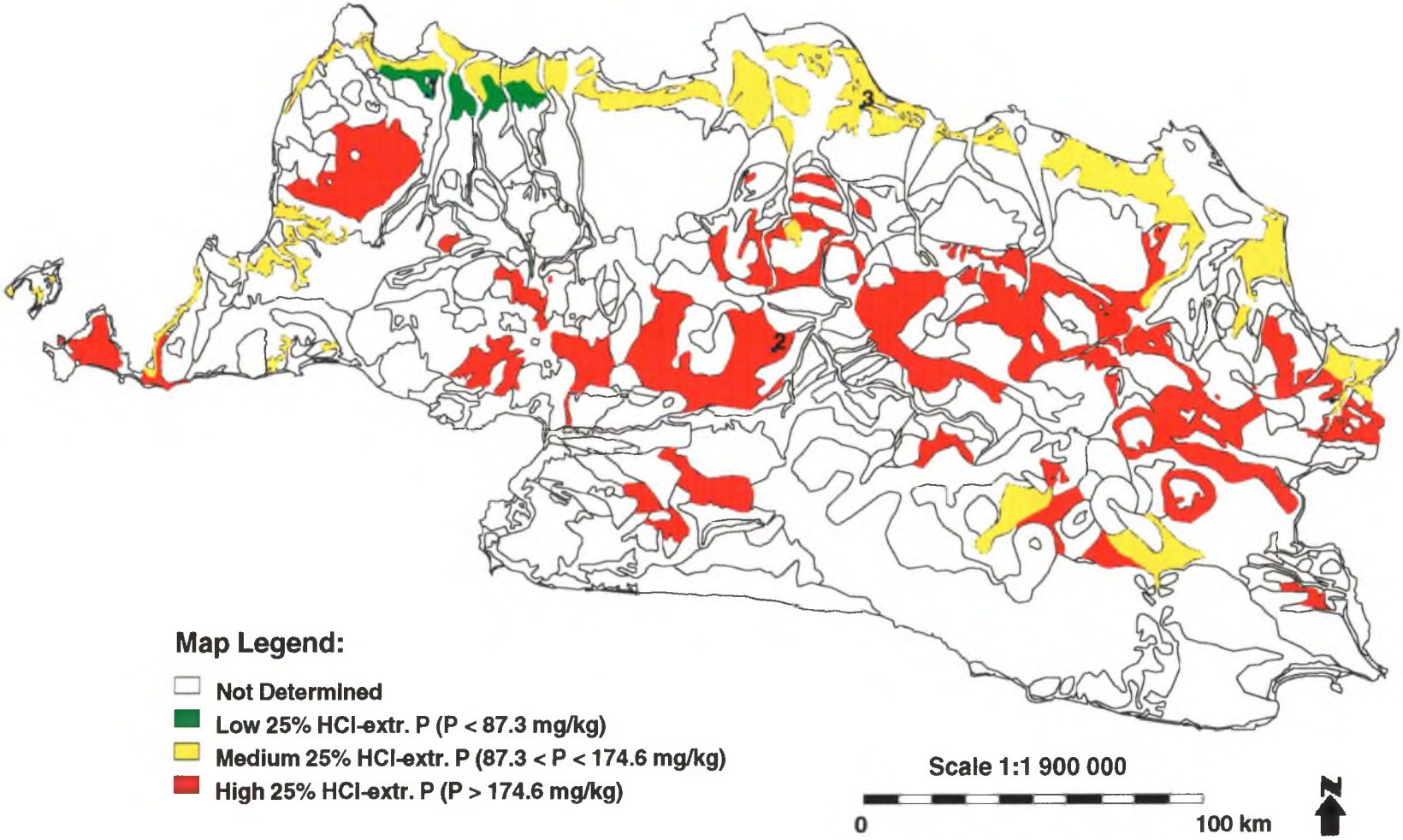


Figure 61. Map of initial HCl-extractable P of West Java soils (105°–108°40' East Longitude and 6°–7°40' South Latitude).

4. 6. 2. Mapping the Predicted Extractable P

The purpose of mapping the predicted extractable P at a given time was to estimate the significance of the change (the decrease) in extractable P after a certain number of rice crops.

By incorporating the selected models for predicting extractable P of both methods, 0.5*M* $NaHCO_3$ and 25% HCl, into an ARC/INFO Macro Language programming (AML) the distribution of predicted extractable P at any given time could be shown as maps. Only the predicted extractable P under the existence of rice crops was mapped. Figures 62 to 64 present the maps of predicted 0.5*M* $NaHCO_3$-extractable P of East Java, Central Java, and West Java, respectively, after 8 crops of rice assuming that the soils were not initially fertilized with P. Similarly, Figures 65 to 67 displayed the HCl-extractable P for East Java, Central Java, and West Java, respectively.

Predicted 0.5*M* $NaHCO_3$ residual extractable P for some soils, such as alluvial soils, association of regosols-lithosols, and association of latosols-lithosols, decreased rapidly from high to low extractable P after 8 crops of rice growth. This was because these soils have relatively high clay physical activity which induced the decrease of 0.5*M* $NaHCO_3$-extractable P faster. Clay physical activity (physical soil property) was one of several significant soil variables that influenced the predicted 0.5*M* $NaHCO_3$ residual extractable P (see equation model 1b in Table 13). There were two types of grumusols in this study, grey grumusols and an association of grumusols-

regosols-lithosols. The predicted 0.5*M* $NaHCO_3$-extractable in the association of grumusols-regosols-lithosols decreased faster than that of grey grumusols. This was probably because the grey grumusol (Purwodadi soil) contained very high amounts of $CaCO_3$ (125.0 g kg^{-1}) which has the capacity to sorb P (Kuo and Lotse, 1972; Samples *et al.*, 1980). This high sorption capacity was also reflected by a relatively low clay physical activity value for this particular grumusol (Uehara and Gillman, 1981).

The categories of the predicted HCl-extractable P status for most of the representative soils did not change, except for the association of grumusol-regosol-lithosol soil that changed from high to medium category.

There are several ways the results of the prediction can be mapped, first to map the change in extractable P, and/or secondly, to map the values of the predicted results. However, the maps of the predicted extractable P over time are more useful compared to maps of the change in extractable P for the decision maker. In this case the decision makers are probably agricultural extension agents who inform farmers not just where but how much P fertilizers should be applied and when to apply it. Moreover, the maps of the predicted extractable P will also be very helpful in assessing regional needs for P fertilizer.

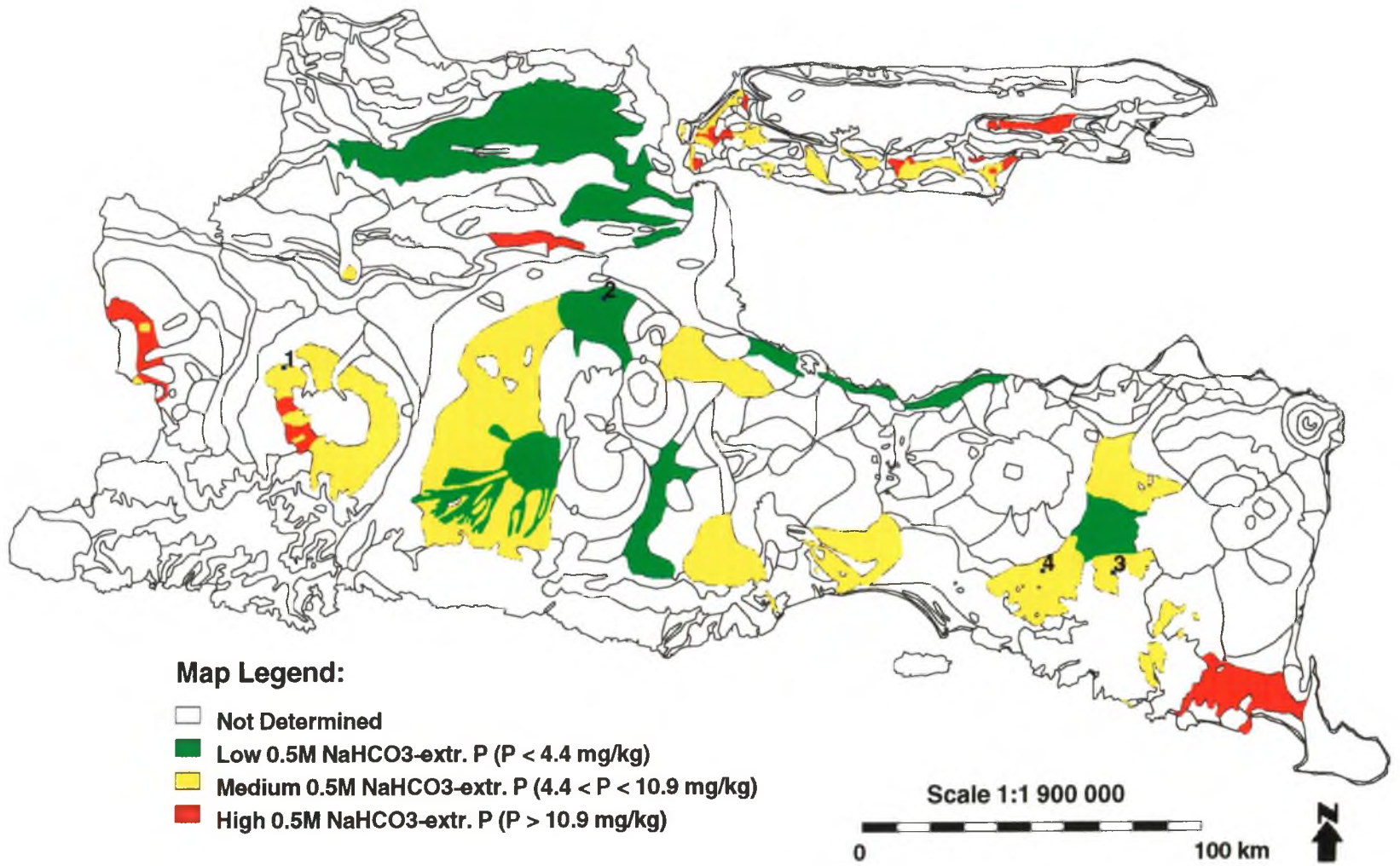


Figure 62. Map of predicted 0.5*M* $NaHCO_3$-extractable P after 8 crops, initially fertilized with 0 kg P ha^{-1} of East Java (111°20'–114°40' East Longitude and 6°40–8°45' South Latitude).

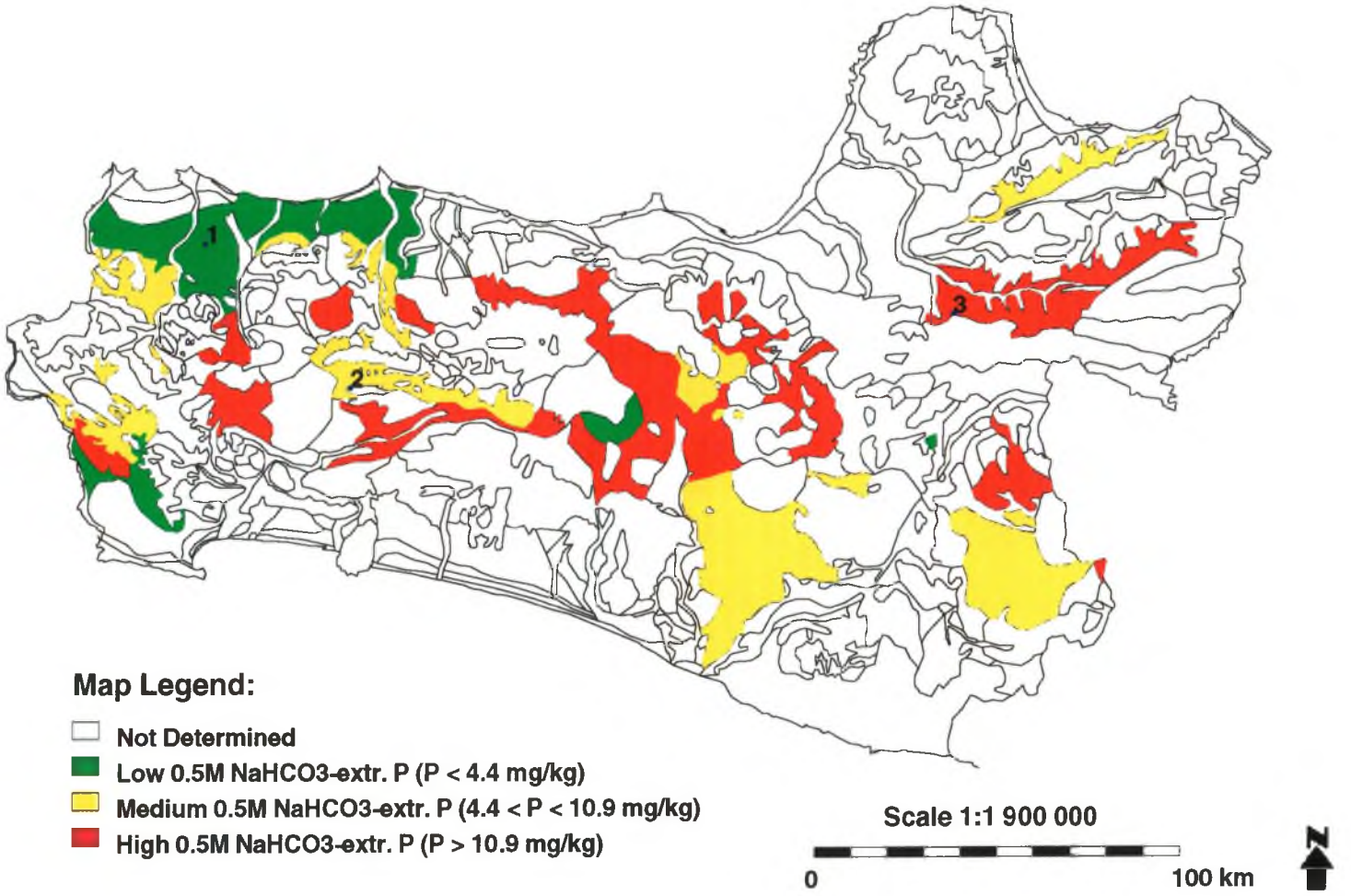


Figure 63. Map of predicted 0.5*M* $NaHCO_3$-extractable P after 8 crops, initially fertilized with 0 kg P ha^{-1} of Central Java (108°40'–111°40 East Longitude and 6°40'–8°20' South Latitude).

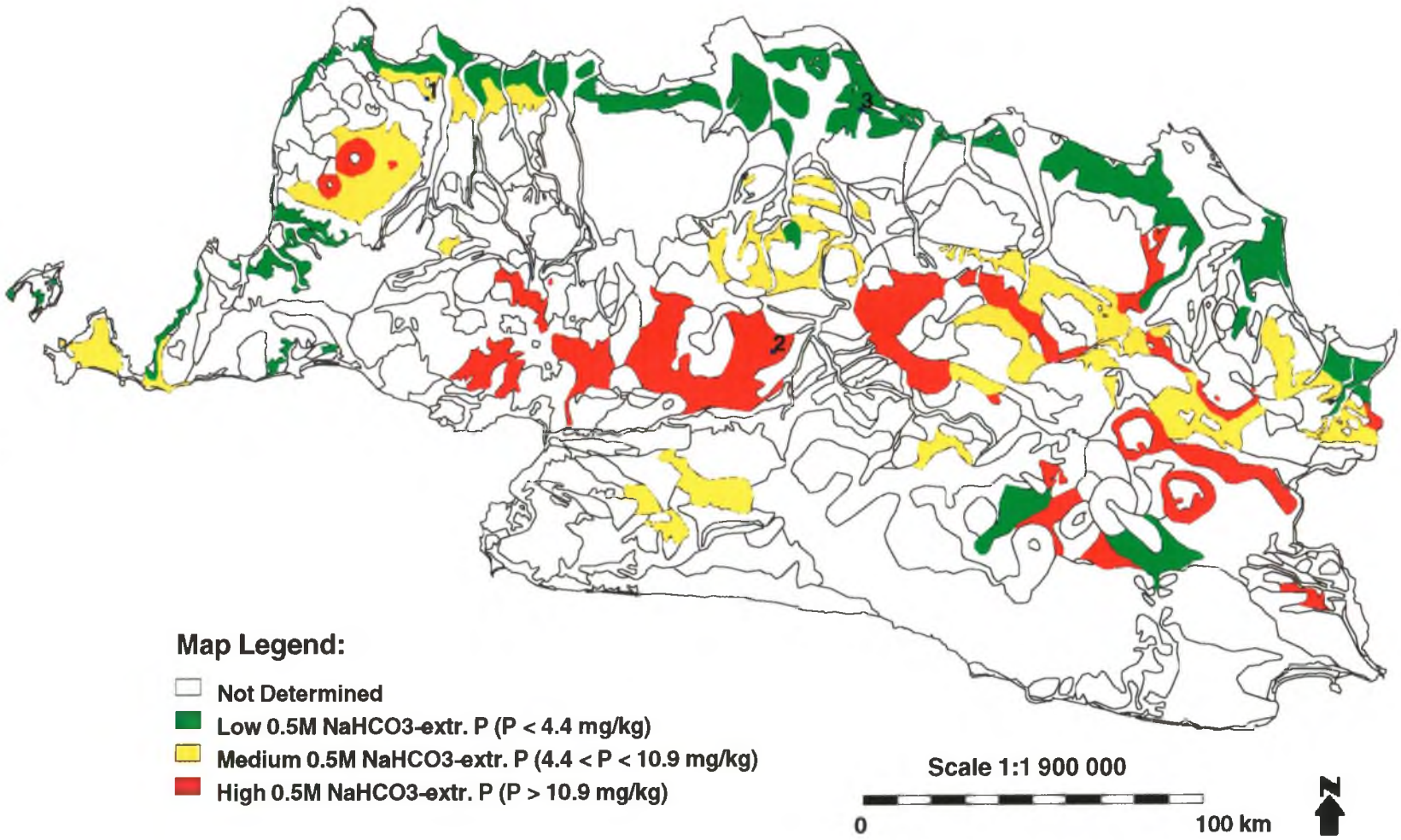


Figure 64. Map of predicted 0.5*M* $NaHCO_3$-extractable P after 8 crops, initially fertilized with 0 kg P ha^{-1} of West Java (105°–108°40' East Longitude and 6°–7°40' South Latitude).

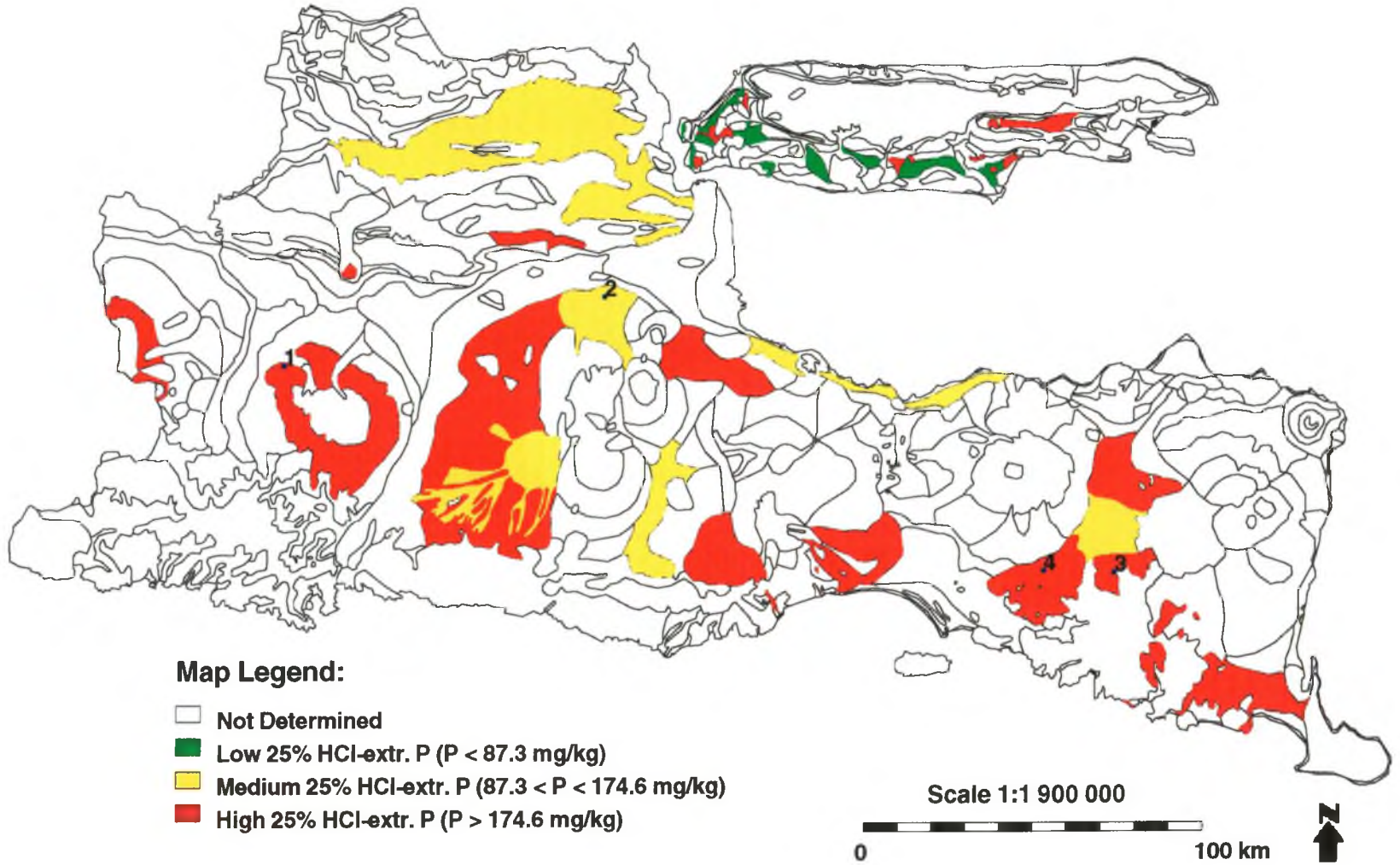


Figure 65. Map of predicted HCl-extractable P after 8 crops, initially fertilized with 0 kg P ha^{-1} of East Java (111°20'–114°40' East Longitude and 6°40–8°45' South Latitude).

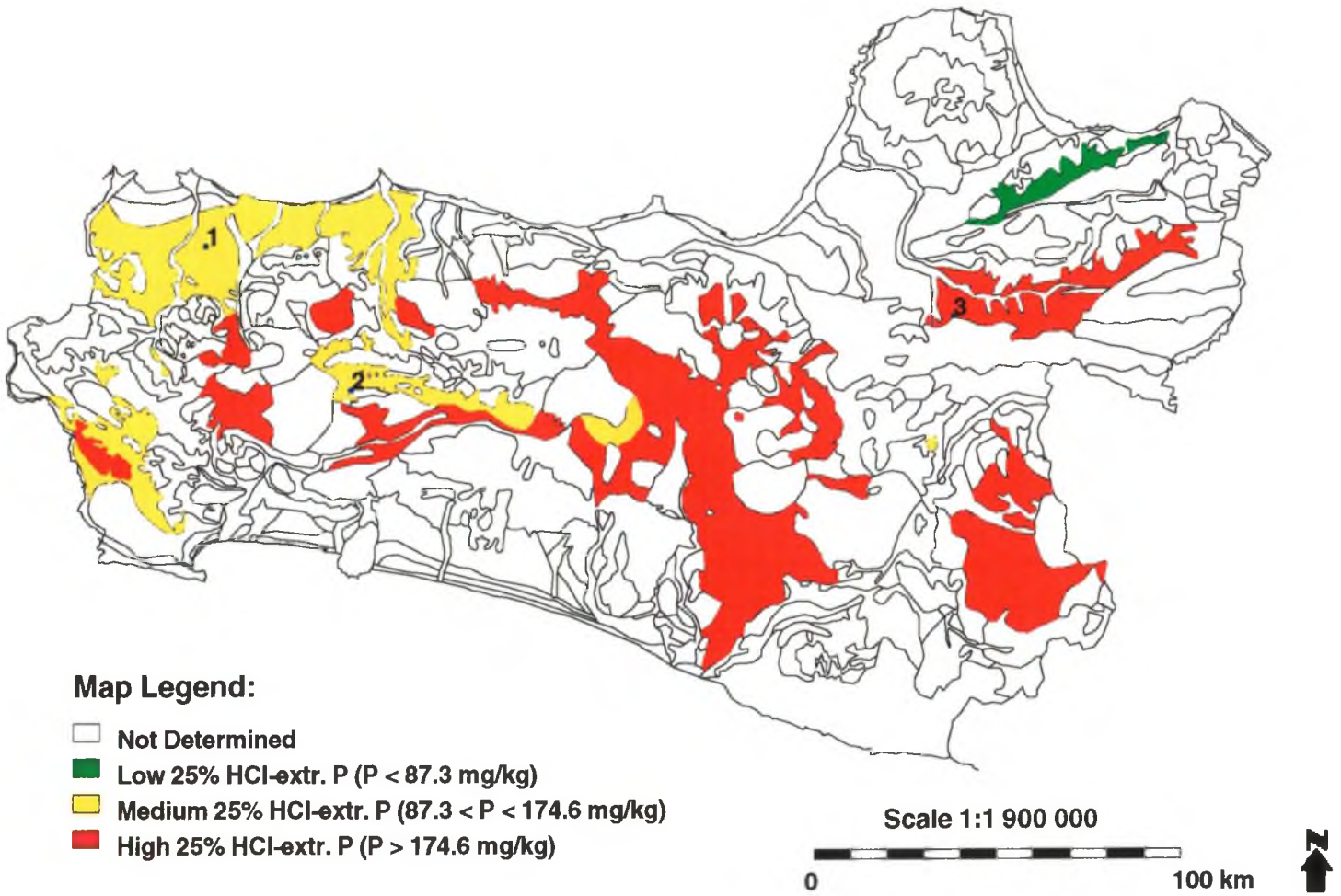


Figure 66. Map of predicted HCl-extractable P after 8 crops, initially fertilized with 0 kg P ha^{-1} of Central Java (108°40'–111°40 East Longitude and 6°40'–8°20' South Latitude).

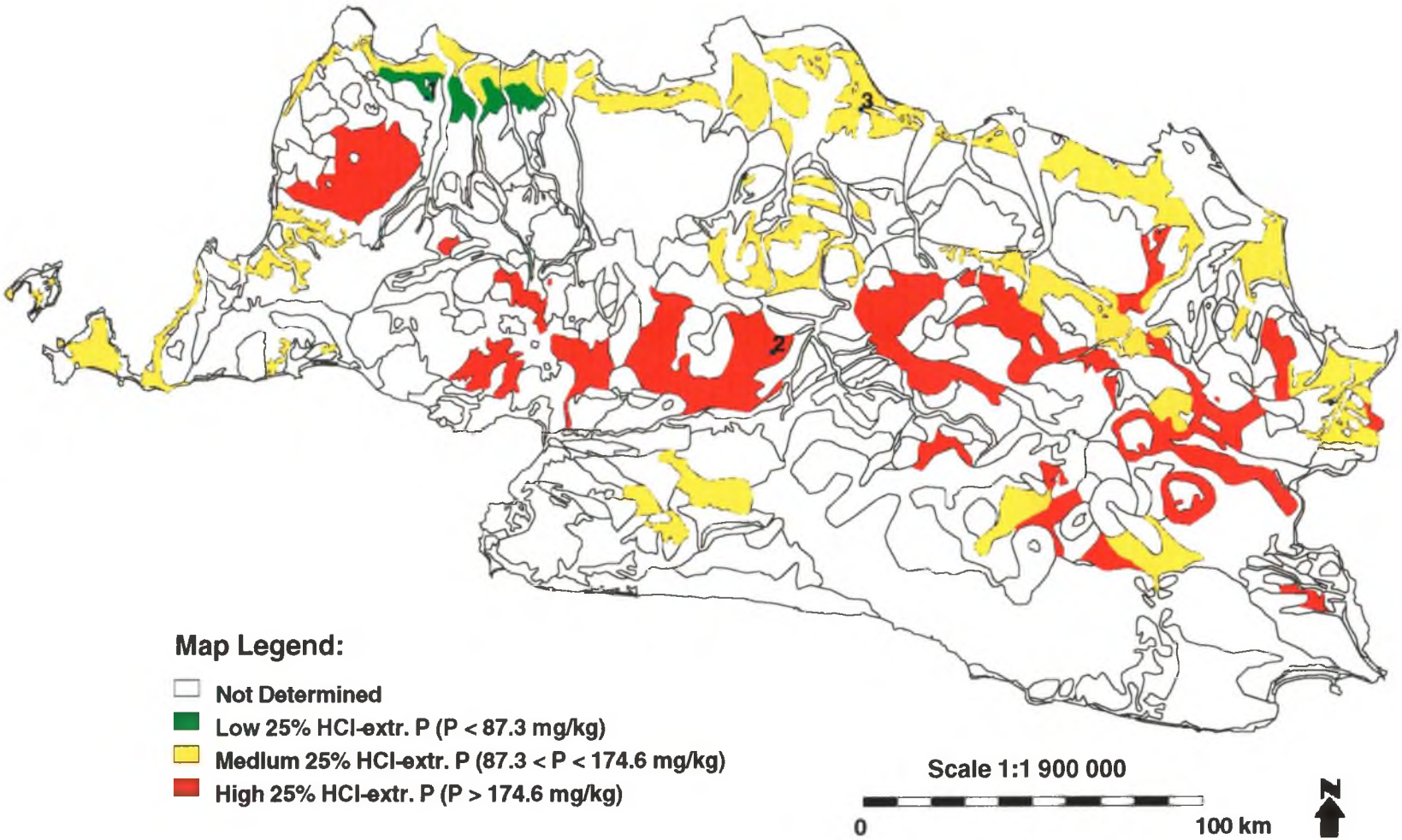


Figure 67. Map of predicted HCl-extractable P after 8 crops, initially fertilized with 0 kg P ha^{-1} of West Java (105°–108°40' East Longitude and 6°–7°40' South Latitude).

CHAPTER 5. CONTRIBUTION OF THIS STUDY TO IMPROVE PHOSPHATE RECOMMENDATIONS IN PADDY SOILS OF JAVA

Triple super phosphate (TSP) and urea have been applied to paddy soils in Indonesia since the 1960s. This was part of government intensification programs such as *BIMAS*, *INMAS*, *IMPROVED BIMAS*, *INSUS*, and *SUPRA-INSUS* to intensify rice productivity.

Notes:
BIMAS. an acronym of ***Bi****mbingan* ***Mas****sal (Mass Guidance), was a government intensification loan package program that included high productivity seeds (PB variety), urea (200 kg of urea per ha) and TSP fertilizers (80 kg of TSP per ha), insecticides & sprayer, spraying costs, transportation cost, and cost of living. Bimas used a group credit approach, in which the credit loans were given to groups of farmers through government institutions. Bimas was applied in 1965 to 1968 (Birowo, 1975; Fakultas Pertanian - Institut Pertanian Bogor, 1992).*

INMAS. an acronym of ***In****tensifikasi* ***Mas****sal (Mass Intensification), was the same as Bimas but provided only technical advices without credit loans to established farmers. All farmers who financed their own farm supplies were considered Inmas farmers. Inmas was practiced in 1967 to 1968 (Birowo, 1975).*

IMPROVED BIMAS. was an improved version of Bimas, which the credit loans were given to farmers individually through village units of Bank Rakyat Indonesia. The loan packages were the same as Bimas plus some amount allocated for rat poison & bait. The common dosage of fertilizer was 200 kg urea per ha and 80 to 125 kg TSP per ha. Improved Bimas was practiced in 1969/1970 to 1979 (Birowo, 1975; Fakultas Pertanian - Institut Pertanian Bogor, 1992).

INSUS. an acronym of ***In****tensifikasi Khu****sus*** *(Specific Intensification), was an extension of Improved Bimas program, which was guided by small core group of farmers. The loan packages were the same as*

Improved Bimas except that PB 36 rice variety was used to replace the previous PB's. And the distribution of all fertilizers was managed by Koperasi Unit Desa (KUD) or Village Unit Cooperative. Insus was applied from 1979 to 1986 (Fakultas Pertanian - Institut Pertanian Bogor, 1992).

SUPRA-INSUS was an extension of Insus program with the application of ten elements of Supra Insus technologies, which were: 1) Cropping system management, 2) Improved soil management, 3) Utilizing high quality and certified seed (blue labeled seeds), 4) Alternate use of different varieties, 5) Applying the proper planting distance, 6) Applying balanced fertilization, 7) Irrigation management at farmers' level, 8) Utilizing foliar fertilizers and growth regulators, 9) Pest and weed control management, and 10) Harvest and postharvest management. Supra Insus was applied from 1986 to date (Fakultas Pertanian - Institut Pertanian Bogor, 1992).

The government policy for P fertilization was one recommendation for all soils which was 100 kg TSP per ha for every rice crop. As a consequence, however, the Centre for Soil and Agroclimate Research of Bogor in 1986 found that continuous application of TSP for almost 30 years caused an accumulation of P in paddy soils (Sri Rochayati *et al.*, 1990). Tables 29 and 30 illustrate the large area affected by this fertilization policy.

Table 29. Area distribution of paddy soil based on HCl-extractable P of Java, in 1974.

Province	Area of paddy soil based on HCl-extractable P status:		
	High	Low	Total
	---------- ha ----------		
West Java	556 400	277 600	834 400
Central Java	547 900	325 100	873 000
East Java	651 500	293 800	945 300
Total	1 755 800	896 500	2 652 300
	(66.20%)	(33.80%)	

Source: Santoso and Sudjadi, 1974.

Table 30. Area distribution of paddy soil based on HCl-extractable P of Java, in 1993.

Province	Area of paddy soil based on HCl-extractable P status:			
	High	Medium	Low	Total
	---------- ha ----------			
West Java	523 384	454 396	235 621	1 213 401
Central Java	397 120	705 766	139 202	1 242 088
East Java	531 475	544 945	183 500	1 259 920
Total	1 451 979	1 705 107	558 323	3 715 409
	(39.08%)	(45.89%)	(15.03%)	

Source: Moersidi *et al.*, 1993.

For the 1974 edition data the area of paddy soils in the high P category also included those in medium P category, since everything above low was considered high. Therefore, it is obvious that after receiving TSP for more than two decades only 15% of the total paddy soil area in Java remained low in extractable P compared

to 34% in 1974. And, if the area of paddy soils of both medium and high categories were combined, there was an increase by approximately 19% in 1993. This also indicates that the use of TSP fertilizer for paddy soils in Java could have been reduced drastically.

Sri Rochayati *et al.* (1990), suggested that TSP fertilization recommendations for paddy soils should be based on the results of field evaluation of fertilization and status of P in paddy soils of Java. Their recommendations, which later became CSAR's (Centre for Soil and Agroclimate Research) were: 1) 125 kg TSP ha^{-1} for paddy soils with low HCl-extractable P (<87.3 mg P kg^{-1}) applied every crop; 2) 75 kg TSP ha^{-1} for paddy soils with medium HCl-extractable P (87.3-175 mg P kg^{-1}) applied once every 2 crops; and 3) 50 kg TSP ha^{-1} for paddy soils with high HCl-extractable P (>175 mg P kg^{-1}) applied once every 4 crops.

Compared to the government recommendations, the CSAR recommendations would save as much as 217 000 tonnes TSP per crop (Sri Rochayati *et al.*, 1990), which is equivalent to 434 000 (for two crops per year) to 651 000 (for three crops per year) tonnes TSP per year. This amount of TSP fertilizers could have been reallocated to the other islands outside of Java, where soils are apparently P deficient. It was estimated that there are 1 million ha of paddy soils outside Java in which productivity could be raised (Sri Adiningsih, 1994).

After it was publicly announced during the Fifth National meeting of Fertilizer Use Efficiency in 1990, the Research & Development Institute of the

Ministry of Agriculture accepted the CSAR recommendation to replace the government recommendations in 1991-1992 (Wibowo, 1993; Sri Adiningsih and Widjaja-Adhi, 1994).

In order to further improve phosphate management for paddy soils, P fertilizer efficiency should be increased. One alternative is through a site specific fertilizer management strategy through which farmers apply P fertilizer only where and when it is needed, and only in the needed amounts. The models resulting from this study could be employed as a preliminary basis for site specific P fertilizer recommendations. The model for predicting HCl-extractable P could be used to develop site specific fertilizer recommendations. There were several reasons why results from HCl-extractable P might be preferred over those from 0.5*M* $NaHCO_3$: 1) 25% HCl-extractable P showed a better relationship with the plant responses, such as total plant dry-weight and total plant P content (Figures 24 to 27); 2) CSAR's recommendations for P fertilizer recommendation which have been accepted as the government recommendation are based upon HCl-extractable P status; and 3) the 0.5*M* $NaHCO_3$-extractable P of most paddy soils used in this study fell into the high category, except for Silo soil which was medium.

The results of predicting change in HCl-extractable/residual extractable P in the presence of rice crops (see Table 18, and Figures 55 to 64) showed that nine of the ten soils studied did not decline below the critical level (87.3 mg kg^{-1}) for 4 crops. Only in the Serang soil (Gley soil, with 19% clay), which was initially low in HCl-

extractable P, was HCl-extractable P predicted to fall below the critical level after week 16. These results suggest that, except for soil low in HCl-extractable P, no additional P fertilization is needed to sustain up to 4 crops of rice.

Scenarios of Improved Recommendation

Two scenarios were developed to test model predictions in improving the existing fertilizer P recommendations.

The first scenario was a conservative one based on the models of this study, which were developed from the results of greenhouse experiments conducted for four crops of rice. This scenario was developed for a four-crop cycle.

The resulting models suggested that only when the soil was low in initial extractable P did the change in extractable P decline below the critical level after the first crop. The results, therefore, suggested that soils with low initial extractable P should be fertilized in every crop. Since there were no significant differences among the P treatments (0, 20, and 40 kg P ha^{-1}, which was equivalent to 0, 100, and 200 kg TSP ha^{-1}) in interaction with soils and time, the recommended P fertilizer rate for soils with low, medium and high HCl-extractable P could be any number between 0 to 200 kg TSP ha^{-1}. The recommended quantity should be minimum but manageable for easy field application in the field. The suggested minimum recommendation is the same as the minimum recommendation of CSAR which was 50 kg TSP ha^{-1}, equivalent to 10 kg P ha^{-1}. Ten kg P ha^{-1} is less than the average P removal of

approximately 40 kg P ha^{-1} $crop^{-1}$, which will draw on residual soil P. The P fertilizer recommendation for the first scenario is: a) 50 kg TSP ha^{-1} for soils with medium and high initial extractable P, applied in every 4 crops; b) 50 kg TSP ha^{-1} for soils low in initial extractable P, applied in every crop.

The second scenario is a more speculative scenario but may be useful in indicating where critical data are needed to improve precision. This scenario is based on the extractable P extrapolated to additional crops with the fitted model. The proposed P recommendations for the second scenario is the same as the first one except that for soils high in initial extractable P, P fertilization would be applied only once every 8 crops. In almost all soils high in P the extractable P would not decline below the critical level even if the decrease in extractable P for 4 crops was doubled (Figures 42, 43; and 86, 87, 88, 89 and 91 in the Appendix E). Thus, the proposed P fertilizer recommendation for the second scenario is: a) 50 kg TSP ha^{-1} for soils high in initial extractable P, applied once every 8 crops; b) 50 kg TSP ha^{-1} for soils medium in initial extractable P, applied once every 4 crops; and c) 50 kg TSP ha^{-1} for soils low in initial extractable P, applied to each crop. Table 31. illustrates that from 85 000 to 94 000 tonnes of TSP per crop (equal to 170 000 to 188 000 tonnes of TSP per two-crop-year) conserved if the improved recommendations would be adopted, compared to that of CSAR/government recommendation.

The proposed recommendations would not only reduce the input of the P fertilizer into, but also should increase the efficiency of P fertilizer use and reduce

farmer's fertilizer costs. Such a reduction in fertilizer cost should be welcomed by farmers since the fertilizer subsidies were ended by the Ministry of Agriculture in October 1994. Triple super phosphate (TSP) was previously subsidized by almost 65% in 1989 but the subsidy was reduced to 30% in 1994 (before October 1994) (Ditjen. Tanaman Pangan, 1994).

Table 31. Effect of proposed P fertilizer recommendations on reducing farmers' and government expenditures.

	Area of paddy soils with various HCl-P status†:			Total fertilizer (TSP) required	Total TSP Saved¶ by proposed recommendation
	High	Medium	Low		
	---------- ha ----------			----- ha -----	--tonnes crop^{-1}--
Total Area	1 451 979	1 705 107	558 323	3 715 409	
	CSAR recommendation‡:			--- tonnes ---	
Recommended P Fert. (kg TSP ha^{-1})	50	75	125		
Frequency of TSP applied per 4-crops	1	2	4		
TSP needed (tonnes 4-crops^{-1})§	72 600	255 800	279 200	607 600	
	Proposed recommendation 1:			--- tonnes ---	
Recommended P Fert. (kg TSP ha^{-1})	50	50	50		
Frequency of TSP applied per 4-crops	1	1	4		
TSP needed (tonnes 4-crops^{-1})§	72 600	85 300	111 700	269 600	84 500
	Proposed recommendation 2:			--- tonnes ---	
Recommended P Fert. (kg TSP ha^{-1})	50	50	50		
Frequency of TSP applied per 8 crops	1	2	8		
TSP needed (tonnes 8-crops^{-1})§	72 600	170 500	223 300	466 400	93 600

†) Source: Moersidi *et al.*, 1993.
‡) Source: Sri Rochayati *et al.*, 1990.
§) Calculated by multiplying the associated total area of paddy soil with the recommended TSP and the frequency of TSP applied.
¶) Calculated by subtracting the total TSP needed of each proposed recommendation from that of the CSAR/government recommendations.

The proposed recommendations above were simplified by considering only the initial extractable P in soils. However, since the prediction model includes soil variables, therefore to further improve recommendations, they could be developed based upon a specific soil basis. This could be prepared by incorporating the prediction model into a spreadsheet, such as QuattroPro®, Lotus123®, Excel®, and etc. Given the soil data required for the model the extractable P could be estimated. Based on the estimated change in extractable P with time, the P fertilizer recommendations for a particular paddy soil could be estimated, see Appendix A for a detailed sample calculation.

CHAPTER 6. CONCLUSIONS AND SUGGESTIONS

6. 1. Conclusions

The soil characteristics, the physical, chemical and mineralogical properties, of the representative paddy soils utilized in this study covered wide range of values. So that, the results of the study can presumably be applied to a wide range of soils.

There is no significant effect of the first and second degree interactions between the amount of P fertilizer applied with the other two factors, soils and crop-time, to the whole-plant dry weight and whole-plant P content. Which indicated that the amount of P fertilizer applied had no significant effect on plant dry weight and plant P content of different soil series and at different crop-time.

The only significant interaction among the studied factors was the soil with time interaction (SoilxTime), which indicated that for in each soil the plant dry weight and plant P content significantly declined over time (crop), especially after the first crop..

Only 25% HCl method of P extraction showed a significant correlation with the plant responses, such as total plant dry-weight and total plant P content. While, the 0.5*M* $NaHCO_3$ (at pH 8.5) method did not reveal any significant correlation with measured plant response.

The decrease in residual extractable P (measured by 0.5*M* $NaHCO_3$ and 25% HCl extractions) in paddy soils under conditions with and without rice can be

predicted by mathematical model. The resulting models reflected soil influences through the soil variables in the models, such as initial extractable P, pH, organic carbon, clay content, and clay physical activity (ratio of plasticity index to clay content) (Table 32).

Clay physical activity was the only variables which always appeared in the nonlinear part of all models that predict the change in extractable P for both methods (0.5*M* $NaHCO_3$ and 25% HCl extractions), under both conditions (with and without the rice). The use of clay physical activity in the models was considerably a new finding compared to the previous studies.

The resulting models were then used to predict site specific P fertilization requirements for paddy soils of Java. For this particular study, however, only the prediction model for HCl-extractable P with rice was used as the basis for P fertilization requirements for paddy soils.

The prediction models for total desorption (TD) and net desorption (ND) of residual P could also be modelled mathematically reflected soil influences by the involvement of frequently measured soil variables in the models. Such frequently measured soil properties were initial extractable P, organic carbon, pH, calcium carbonate, clay content, and clay physical activity.

The resulting model that predicts change in extractable P were then implemented into a geographical information system (GIS) software, ARC/INFO, to predict and map the predicted extractable P over time. Map format presentations

Table 32. Summary of the selected models for predicting 0.5*M* $NaHCO_3$- and 25% HCl-extractable P.

The general prediction model is $EP_t = (a\ EP_i - P_{eq}) + (b\ X) + (c\ X\ P) + \{d\ X\ Exp(-(k0 + k1\ X)\ Time)\}^{\dagger}$,

|<-----linear part ----->| |< --- Nonlinear part --- >|

Prediction Model for:	Linear part of the model:								Nonlinear part of the model:				
	a		Single variable b			Interaction with P c			d			Exponential part	
	EP_i	P_{eq}	OC	PH	CAT	OC	PH	CLAY	OC	PH	CLAY	k0	k1*CAT
$NaHCO_3$-P without crops	-0.34	0.00	-	2.87	-	-	0.015	-	4.26	-	-	-0.23	0.51
$NaHCO_3$-P with crops	-0.25	-26.55	-	-	-21.26	-	-	-0.0002	-	2.21	-	0.13	0.02
25% HCl-P without crops	0.65	0.00	36.22	-	-	0.29	-	-	-	-	0.82	-0.15	0.26
25% HCl-P with crops‡	0.67	11.63	22.26	-	-	-	-	0.006	59.13	-	-	-0.14	0.32

†) where X is replaced by a soil property.

‡) Only prediction model for HCl-P with crops was used as the basis to improve P recommendation for paddy soils.

provided a simpler way to describe the change in extractable P of paddy soils spatially. So that, the extension agents and farmers can decide where, when, and what appropriate amount of P fertilizer should be applied.

Approximately 85 000 to 94 000 tonnes of TSP per crop for paddy soils of Java can be saved compared to that of present CSAR/government recommendations, if the proposed first and second scenarios to improve P fertilizer recommendations are followed, respectively. Consequently, the improved recommendations can reduce over-application and minimize cost of P fertilization for paddy soils, as well as environmental impact.

6. 2. Suggestions

Two groups of suggestions are provided in relation to what have been learned and resulted from this study. First group of suggestions are for P recommendations, and second group are for future research.

1. Suggestions for P recommendations

a. P fertilizer recommendations cannot be generalized for all soils, but have to be site specific. P recommendations also need to be evaluated periodically because the amount of residual P in the residual P pool which presumably supports the extractable P pool will not last forever.

b. Since a site specific management requires soils data, therefore access to soils data and soil testing facilities are important and have to be made facile.

c. The P fertilizer saved from the use of Java paddy soils should be reallocated to other islands outside of Java where soils are apparently P deficient.

2. Suggestions for future research

a. The resulting prediction model needs to be verified using field data.

b. In order to improve the prediction change in residual extractable P of paddy soils the number of crops to be evaluated should have been more than four crops, optimally until the rice plant showing P deficiency symptoms.

c. In order to enhance the desorption from the residual P pool that support the extractable P pool, some techniques or methods that enhance the P desorption should be considered. Possible consideration is the use of organic materials, e.g., green manures and/or animal wastes. However, further research must be conducted in relation with the effect of organic materials application on P sorption-desorption in paddy soils.

d. In relation to the technical procedure, the method of measuring extractable P in paddy (flooded) soils needs to be improved. So that, there would be a better relationship between extractable P with the plant responses.

APPENDIX A. APPLYING THE PREDICTION MODEL FOR SITE SPECIFIC P FERTILIZER RECOMMENDATIONS IN PADDY SOILS

1. Install the mathematical model that predicts extractable P into a spreadsheet type of software, such as QuattroPro, Excel, Lotus123, as follows:

The model that will be used to calculate extractable P:

1). General form:

$$EPt = (b0\ HClPi - b1) + b2\ OC + b3\ CLAY\ P + b4\ OC\ Exp\ (-(k0 + k1\ CAT)\ Time)$$

2). Actual form:

$$EPt = (0.67\ HClPi - 11.63) + 22.26\ OC + 0.006\ CLAY\ P + 59.13\ OC\ Exp\ (-(-0.14 + 0.32\ CAT)\ Time)$$

[where: EPt is the predicted extractable P (mg kg^{-1}) a given time, HClPi is the initial HCl-extractable P (mg kg^{-1}), OC is organic carbon content (%), CLAY is the clay content (%), P is the amount of P fertilizer applied (kg P ha^{-1}), and CAT is the physical clay activity (unit less); b0 to b4 are the coefficients of the model, k0 and k1 are the loss constants; and Time is in weeks].

Input each of the above model coefficients into a spreadsheet cells, as follows:

Table 1. Spreadsheet format of inputting the coefficients of model describing the decline in soil P with time.

	A	B	C	D	E	F	G
1 2	b0 (HClPi)	b1	b2 (OC)	b3 (CLAY*P)	b4 (OC*EXP)	k0	k1 (CAT)
3	0.67	11.63	22.26	0.006	59.13	-0.14	0.32

2. Provide the necessary soil data needed in the model into a spreadsheet page (Table 2).
e.g.: initial 25% HCl-extractable P (HClPi), clay content (CLAY), organic carbon content (OC), physical clay activity (CAT).

Table 2. Soil data required for model to describe the decrease in soil P with time.

	A	B	C	D	E	F	G	H
11	Soil	HClPi	OC	CLAY	CAT	P Appl.	EP_t (Week)	
12		(mg/kg)	(%)	(%)		(kg P/ha)	0	1
13	Soil 1	226.26	1.30	50.0	0.77	10	...	...
14	Soil 2	506.48	1.95	54.0	0.52			
15	Soil 3	82.96	1.49	19.0	0.81			
16	:	:	:	:	:			
17	:	:	:	:	:			

3. Estimate the extractable P (EPt) for 4 crops (44 weeks) by utilizing the values of the model coefficients (Table 1) and soil data (Table 2) into the EPt model formula in cells G13 to AL13 of Table 2. (See Step 2 and 3 in Sample Calculation)

4. Calculate the change in extractable P during 4 crop cycle by subtracting EP_t at week 44 from EP_t at week 0 (G13 – AL13). This value is considered as the change in extractable P in every 4 crops.

5. Determine how many crops (or weeks) until the initial HCl-extractable P will fall below the critical level of HCl-P. This is calculated by first subtracting the HCl-extractable P at time 0 with the critical level of HCl-P for rice then divided by the change in extractable P for 4 crops (value of Step 4) and multiply the result by four. This final result indicates how many crops the initial HCl-extractable P will reach critical level.

   {(Initial HCl-P – Critical level)/(value of Step 4)} * 4

6. The results from Step 5 is then used as the basis for P fertilization management.

Sample Calculation:

Step 1. Input each of the model coefficients (b0, b1, b2, b3, b4, k0 and k1) into spreadsheet cells (A2..G2).

	A	B	C	D	E	F	G
1	b0	b1	b2	b3	b4	k0	k1
2	(HClPi)		(OC)	(CLAY*P)	(OC*EXP)		(CAT)
3	0.67	11.63	22.26	0.006	59.13	-0.14	0.32

Step 2. Given Soil-1 data as follows (B13..E13):

	A	B	C	D	E	F	G	H	I	...	AK	AL
11	Soil	HClPi	OC	CLAY	CAT	P Appl.	EP_t at week:					
12		(mg/kg)	(%)	(%)		(kg P/ha)	0	1	2	...	43	44
13	Soil 1	226.26	1.30	50.0	0.77	10	249.0†	241.6	234.9	...	173.2	173.1
14	Soil 2	506.48	1.95	54.0	0.52		...	...	...	...	...	...
...	...	...	...	...	...		...	...	...	...	...	...
20	Change in extractable P :			(G13-AL13) =			75.98					
21	The number of crops :			((G13-87.5‡)/G20)*4 =			8.5					

†) G13 = ((A3*B13) - B3) + (C3*C13) + (D3*D13*F13) + (E3*C13*@EXP(-(F3 + G3*E13)*G12))

‡) 87.5 (in mg P/kg) is the critical level of 25% HCl-P for rice in paddy soils

Step 3. Calculate HCl-extractable P for Soil-1 at any given week up to 44 weeks (4 crops), (G13 .. AL13), see spreadsheet at step 2.

Step 4. The change in extractable P during 4 crops of rice cultivation decreased by as much as:

G20 = (G13 - AL13) = (249.04 - 173.06)
= 75.98 mg P/kg.

Step 5. Thus, HCl-extractable P in this particular soil can support rice up to:

G21 = ((G13-87.5)/G20)*4 = ((249.04 - 87.5)/75.98) x 4
= 8.5 crops.

(Note: 87.5 is the critical level of HCl-extractable P for rice in paddy soils).

Step 6. Therefore, P fertilizer may not be needed until the 9th crop, at which time the minimum application of 50 kg TSP ha^{-1} (see explanation in Scenario on Improved Recommendation of Chapter 5) would be recommended, then resume site specific or soil-based recommendations.

APPENDIX B. FIGURES 68 TO 73. OBSERVED AND PREDICTED 0.5*M* $NaHCO_3$-EXTRACTABLE P WITHOUT RICE

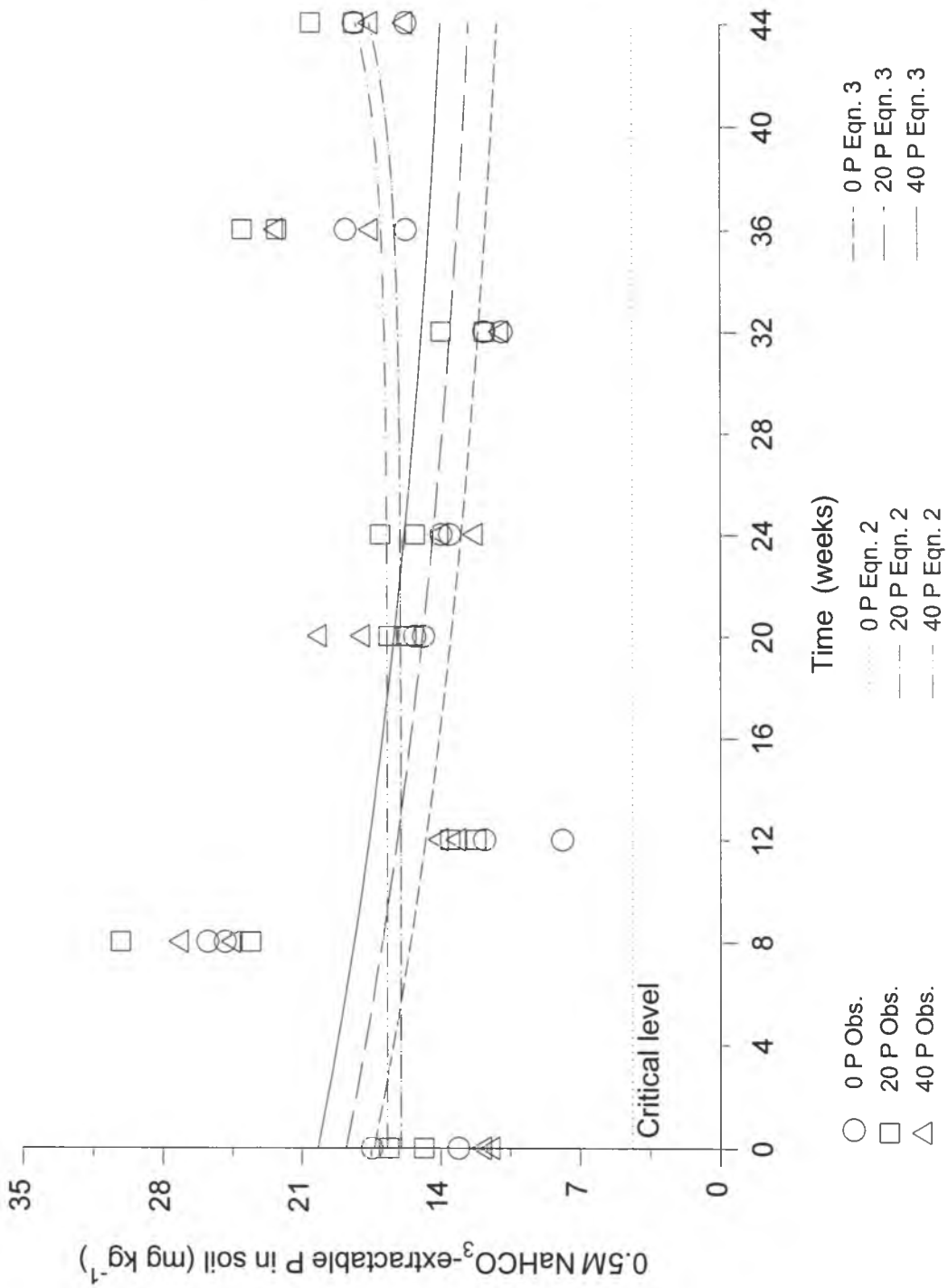


Figure 68. Observed and predicted 0.5*M* $NaHCO_3$-extractable P of Cianjur soil without rice crops.

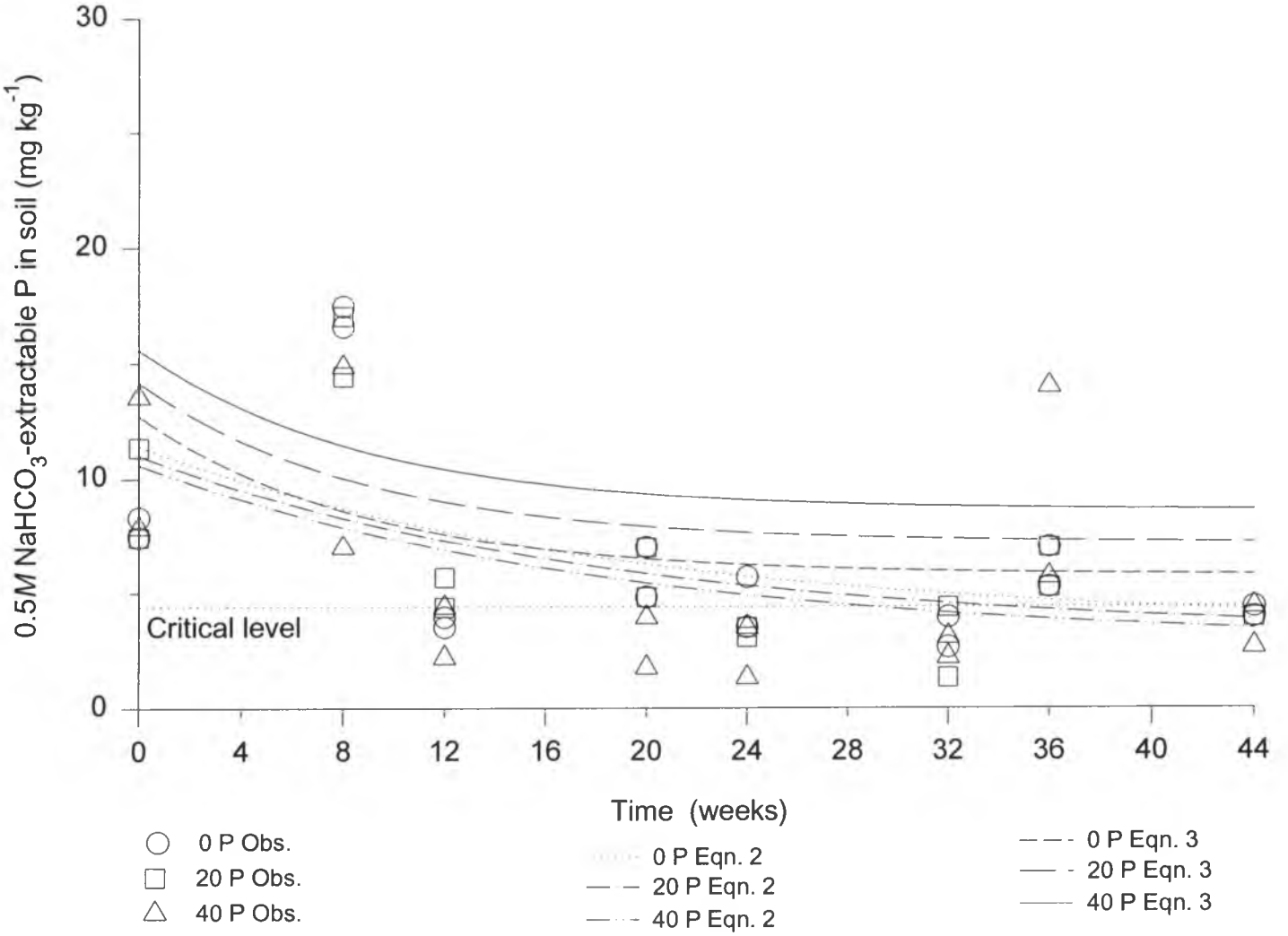


Figure 69. Observed and predicted 0.5*M* $NaHCO_3$-extractable P of Purbalingga soil without rice crops.

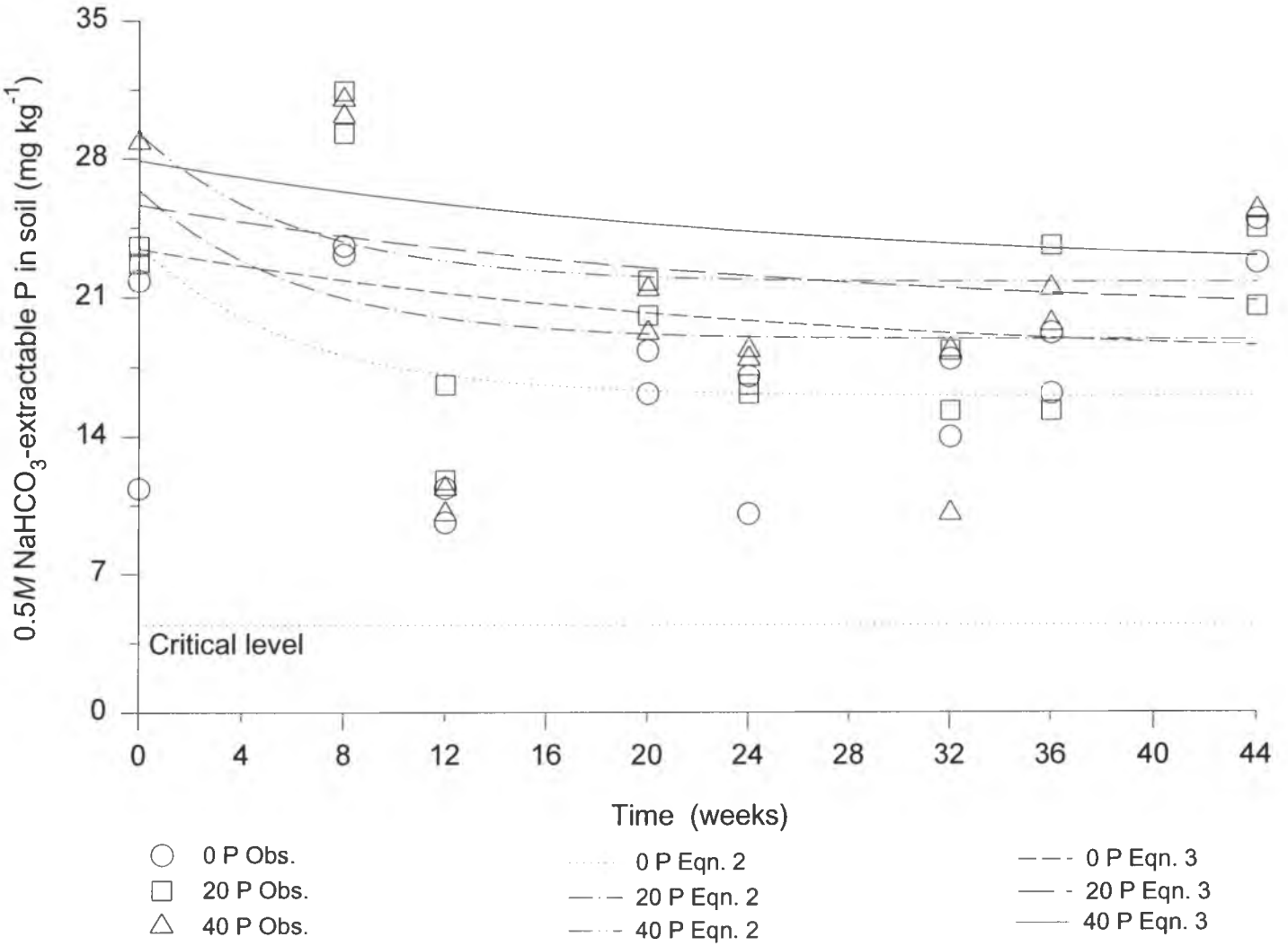


Figure 70. Observed and predicted 0.5*M* $NaHCO_3$-extractable P of Purwodadi soil without rice crops.

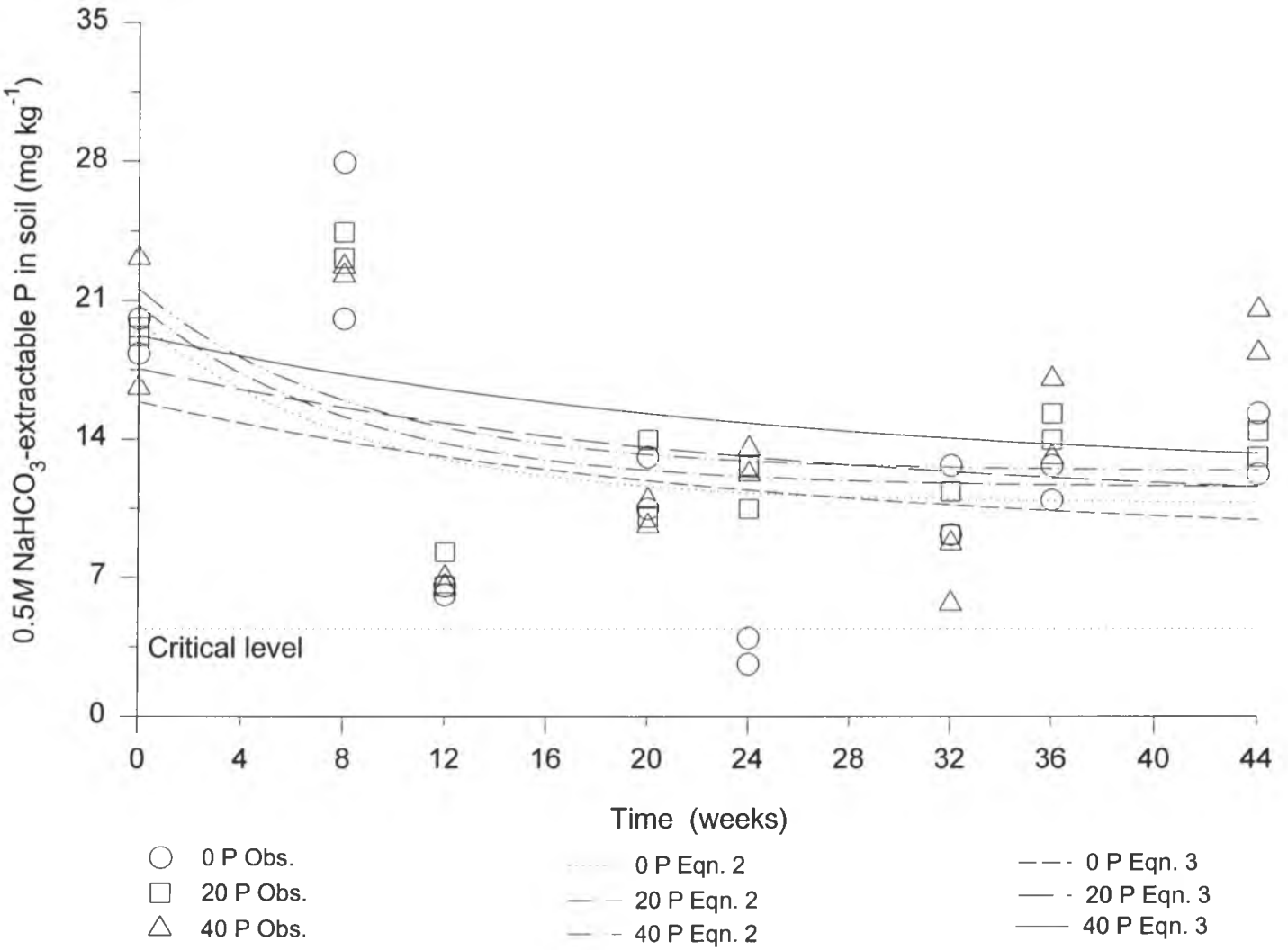


Figure 71. Observed and predicted 0.5*M* $NaHCO_3$-extractable P of Madiun soil without rice crops.

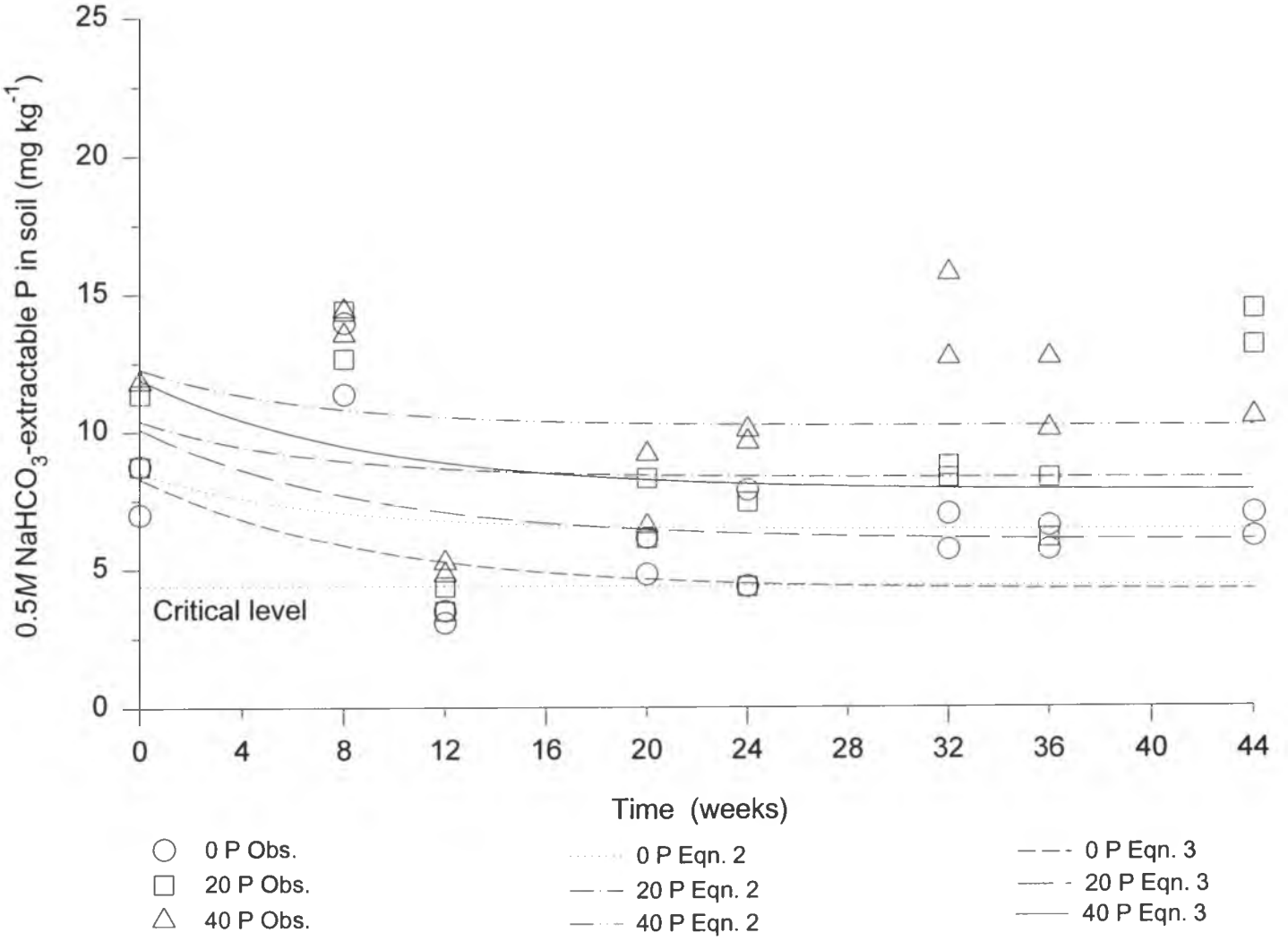


Figure 72. Observed and predicted 0.5*M* $NaHCO_3$-extractable P of Mojokerto soil without rice crops.

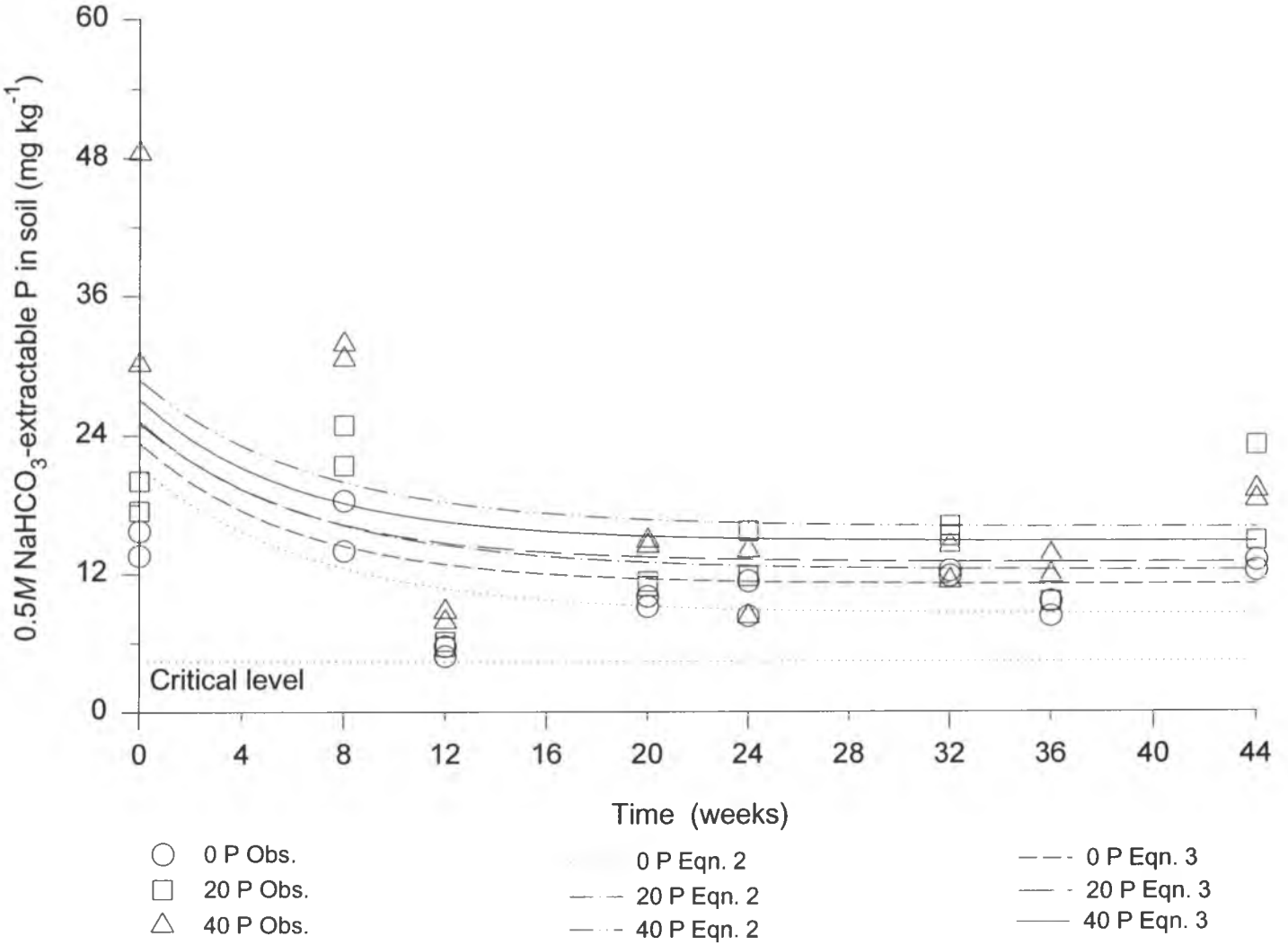


Figure 73. Observed and predicted 0.5*M* $NaHCO_3$-extractable P of Jenggawah soil without rice crops.

APPENDIX C. FIGURES 74 TO 79. OBSERVED AND PREDICTED 0.5*M* $NaHCO_3$-EXTRACTABLE P WITH RICE.

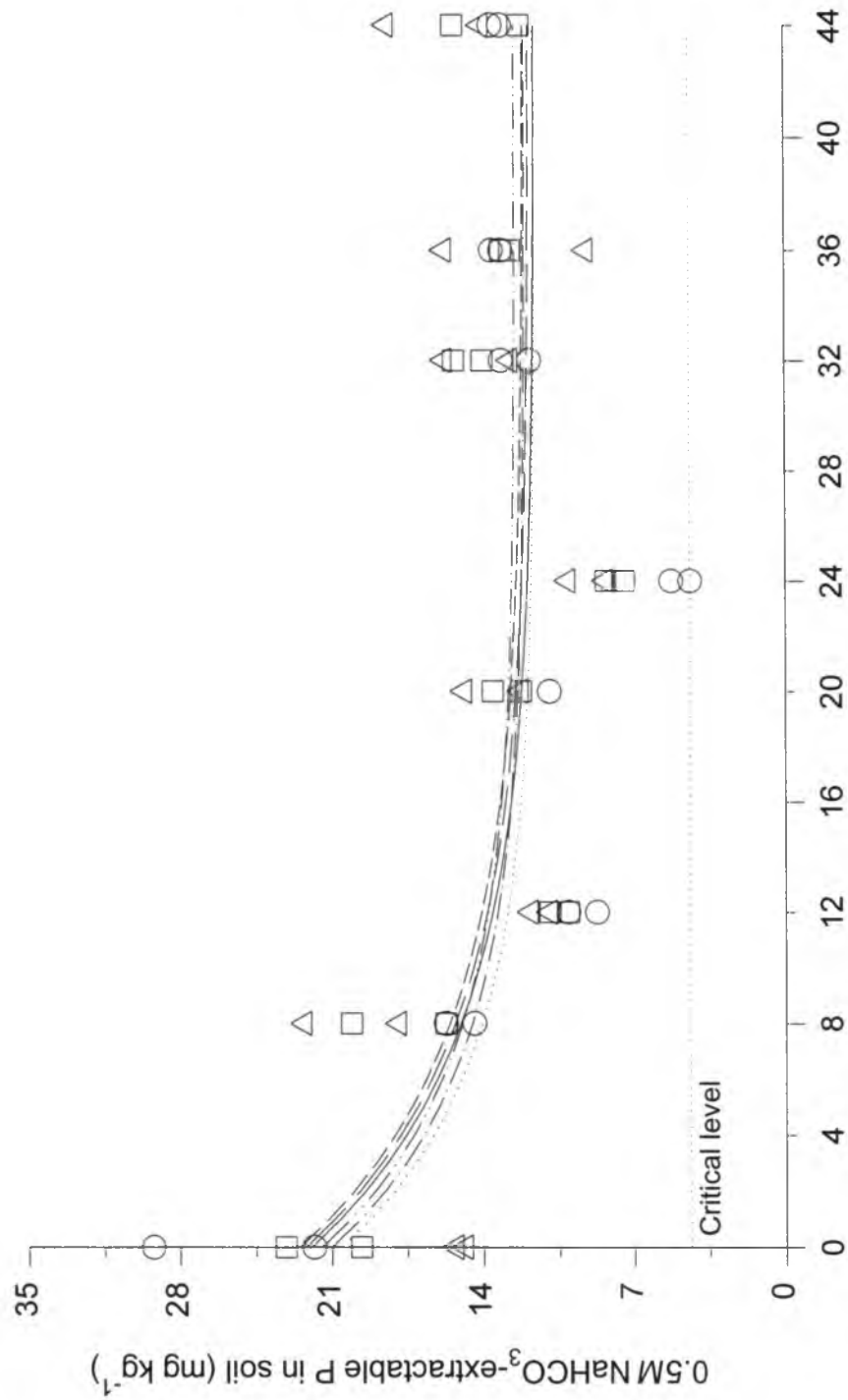


Figure 74. Observed and predicted 0.5*M* $NaHCO_3$-extractable P of Cianjur soil with rice crops.

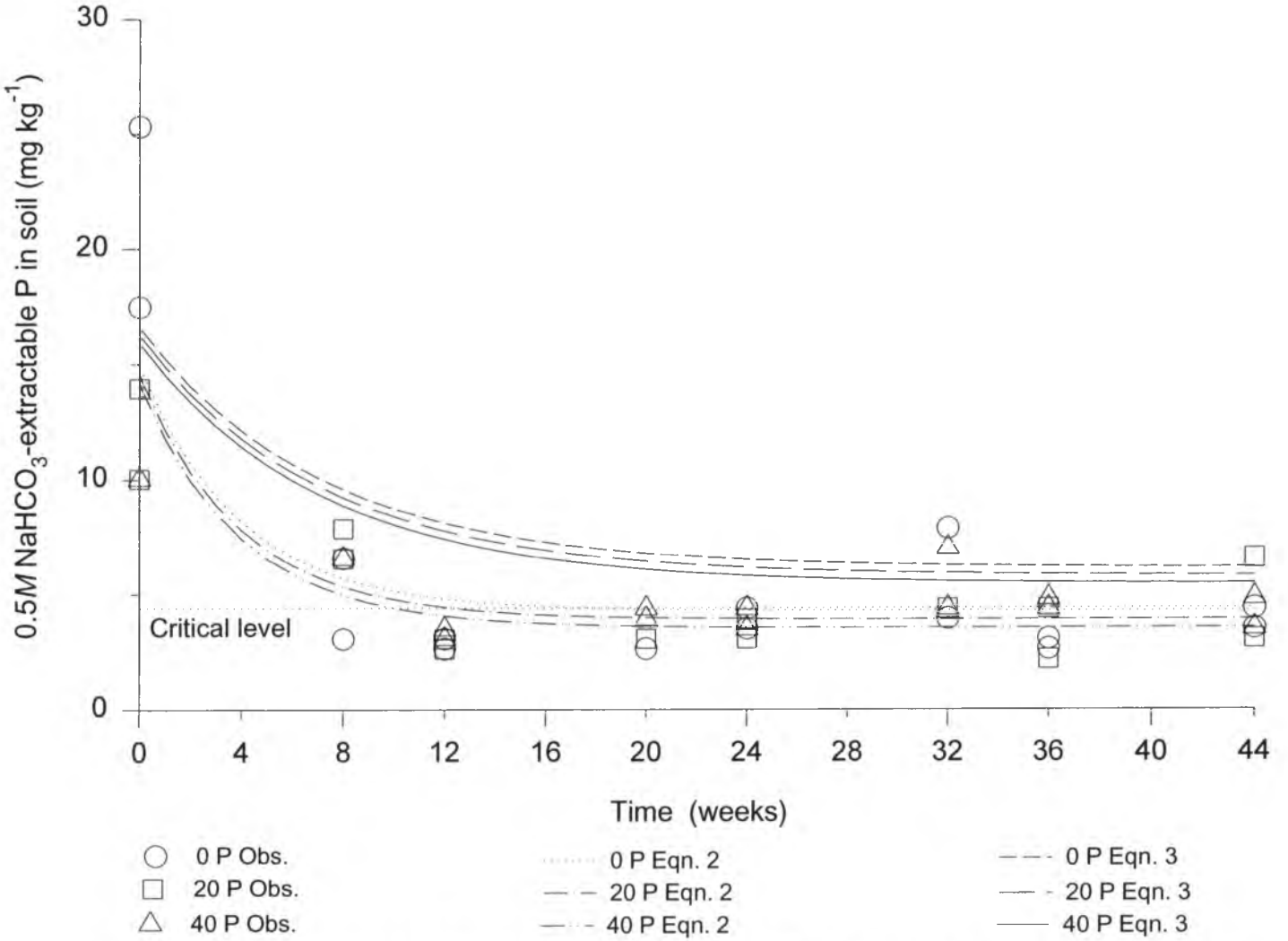


Figure 75. Observed and predicted 0.5*M* $NaHCO_3$-extractable P of Purbalingga soil with rice crops.

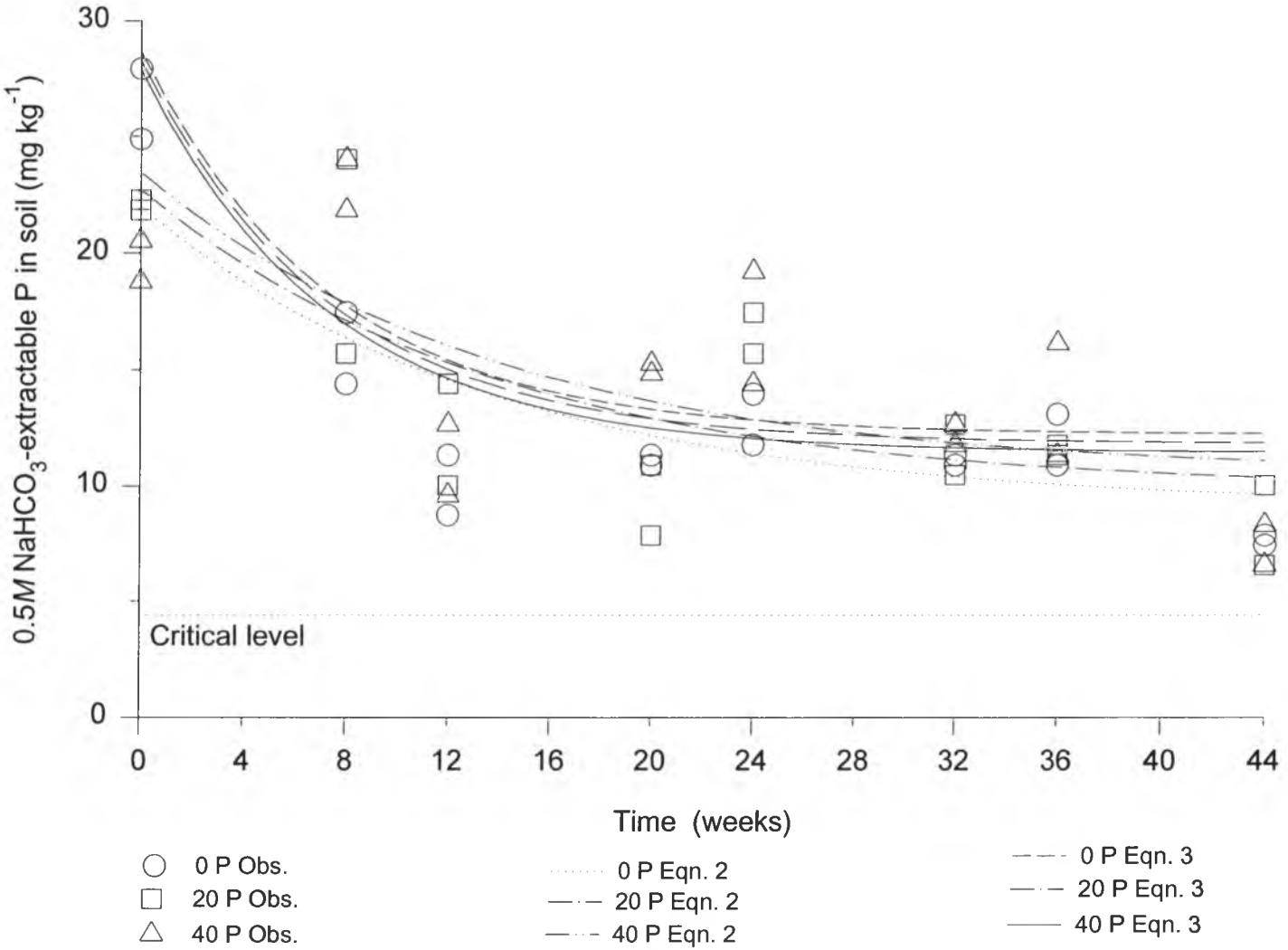


Figure 76. Observed and predicted 0.5*M* $NaHCO_3$-extractable P in Purwodadi soil with rice crops.

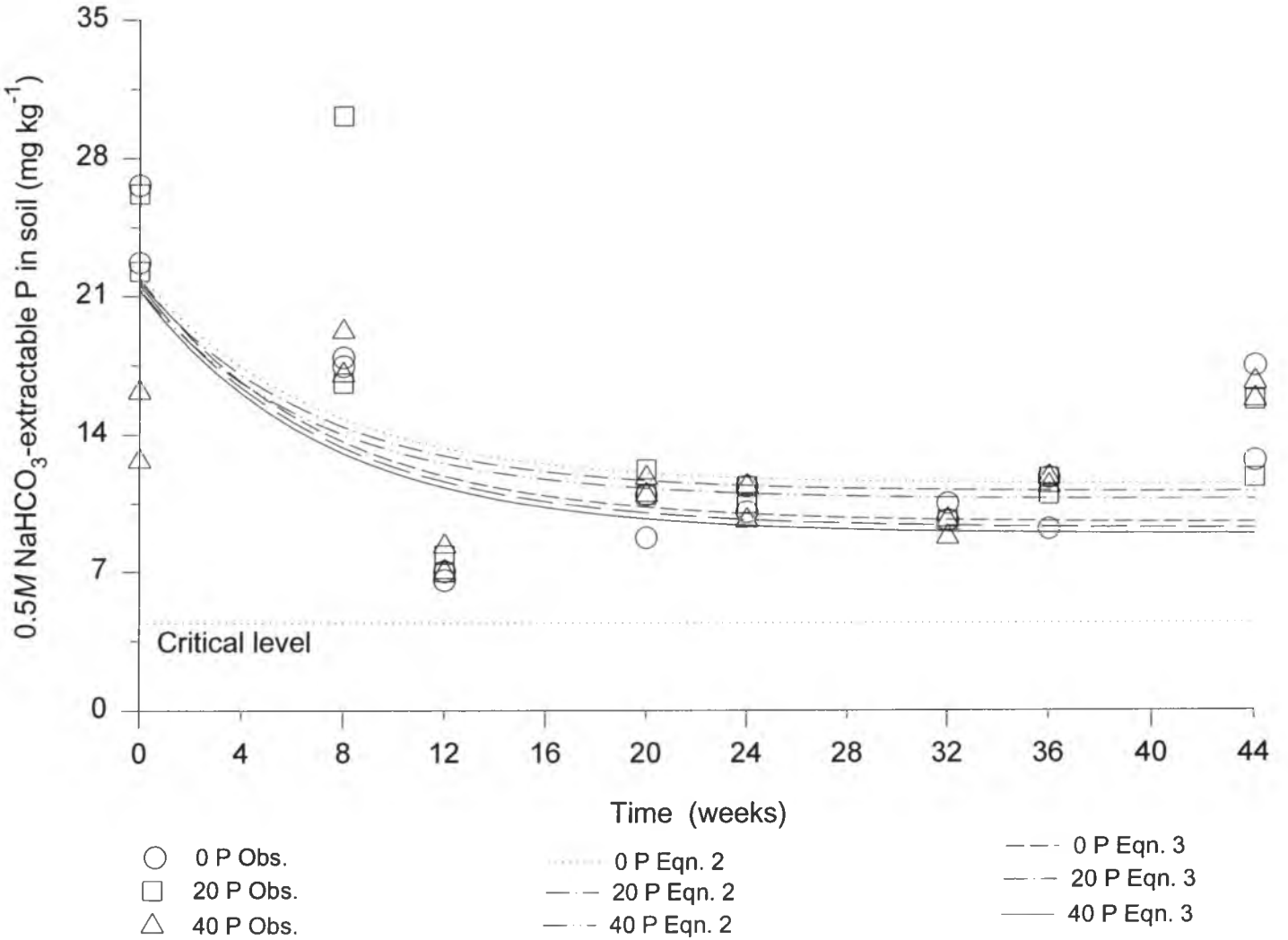


Figure 77. Observed and predicted 0.5*M* $NaHCO_3$-extractable P in Madiun soil with rice crops.

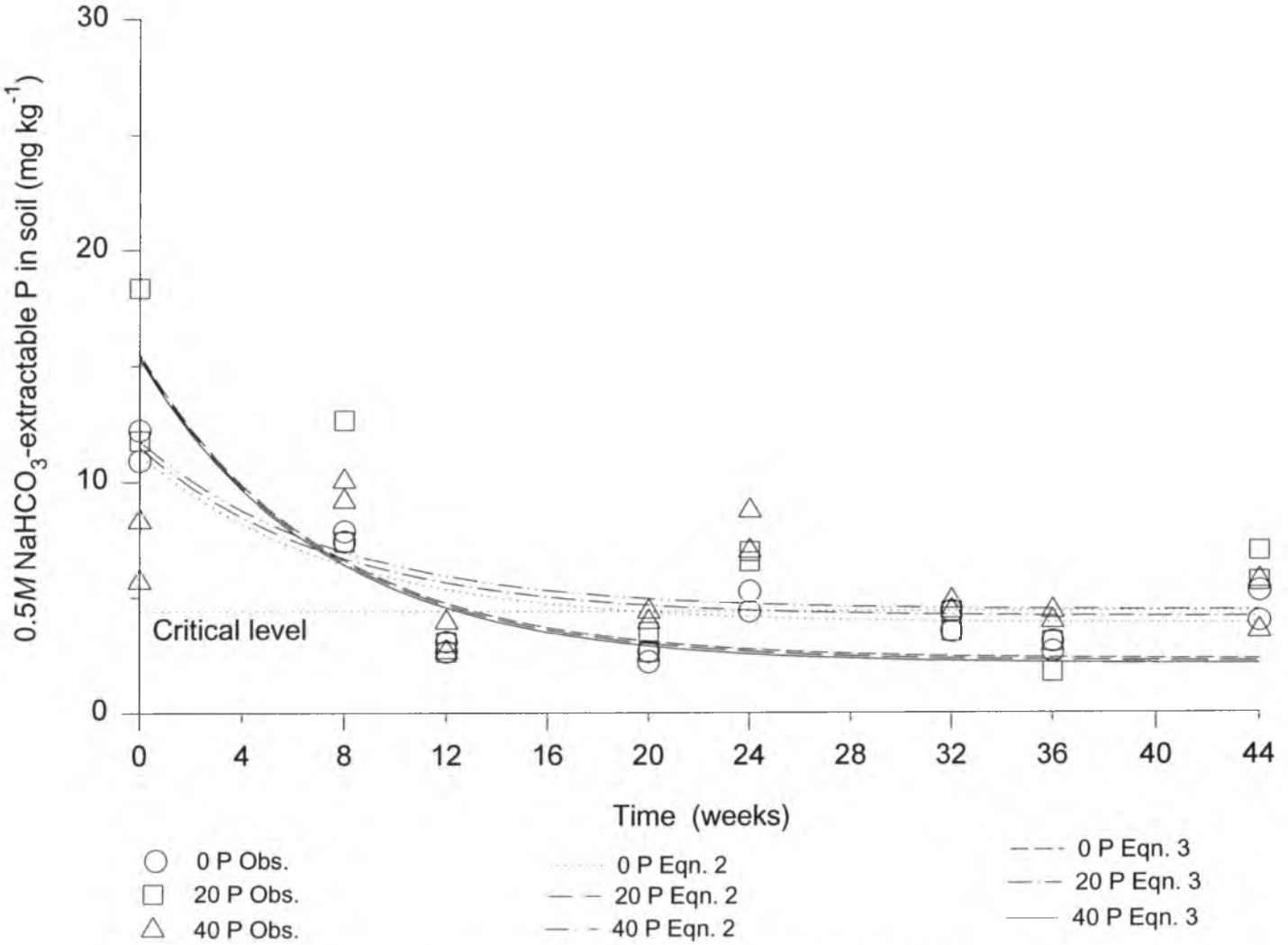


Figure 78. Observed and predicted 0.5*M* $NaHCO_3$-extractable P in Mojokerto soil with rice crops.

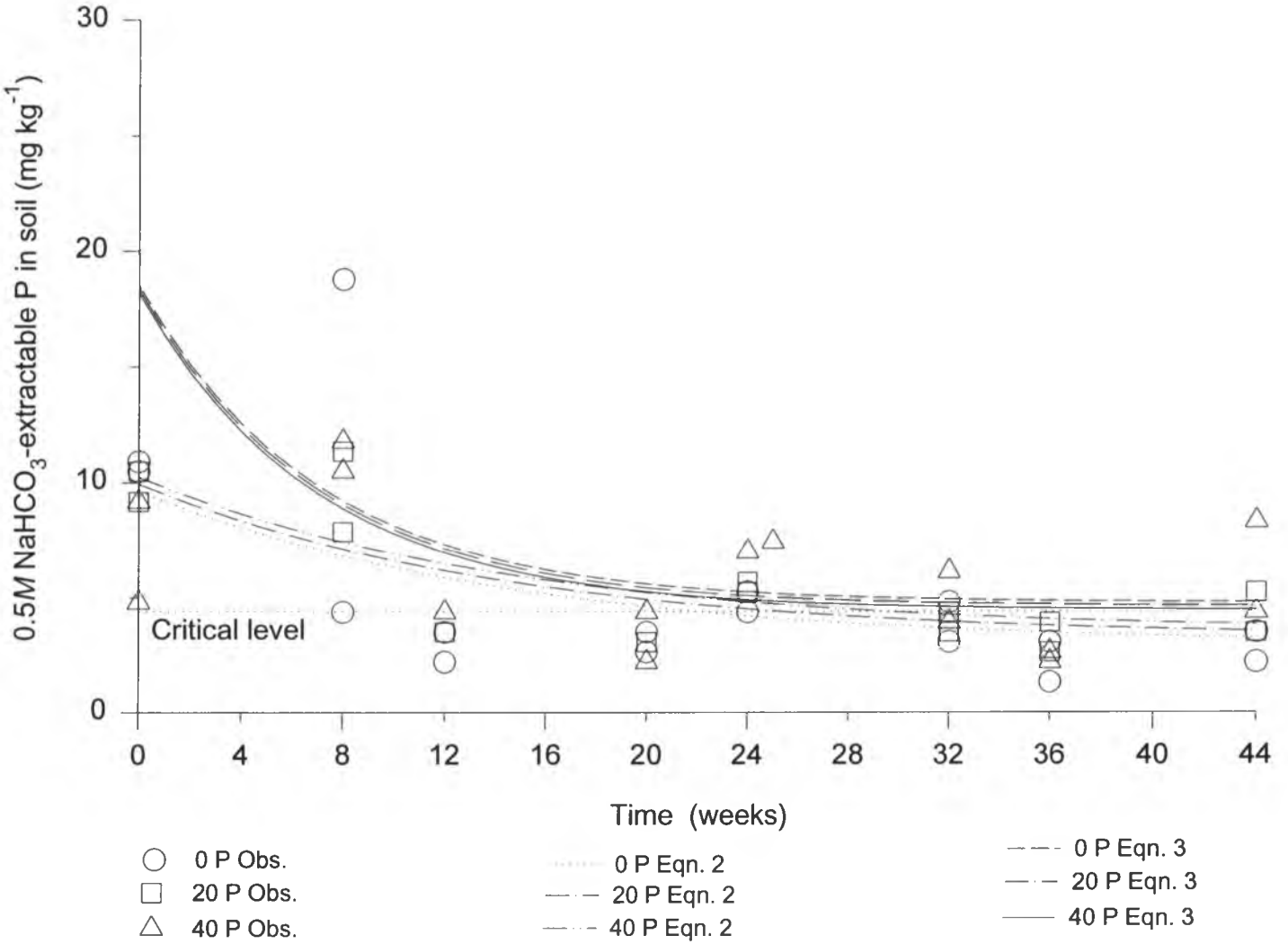


Figure 79. Observed and predicted 0.5*M* $NaHCO_3$-extractable P in Jenggawah soil with rice crops.

APPENDIX D. FIGURES 80 TO 85. OBSERVED AND PREDICTED 25% HCl-EXTRACTABLE P WITHOUT RICE

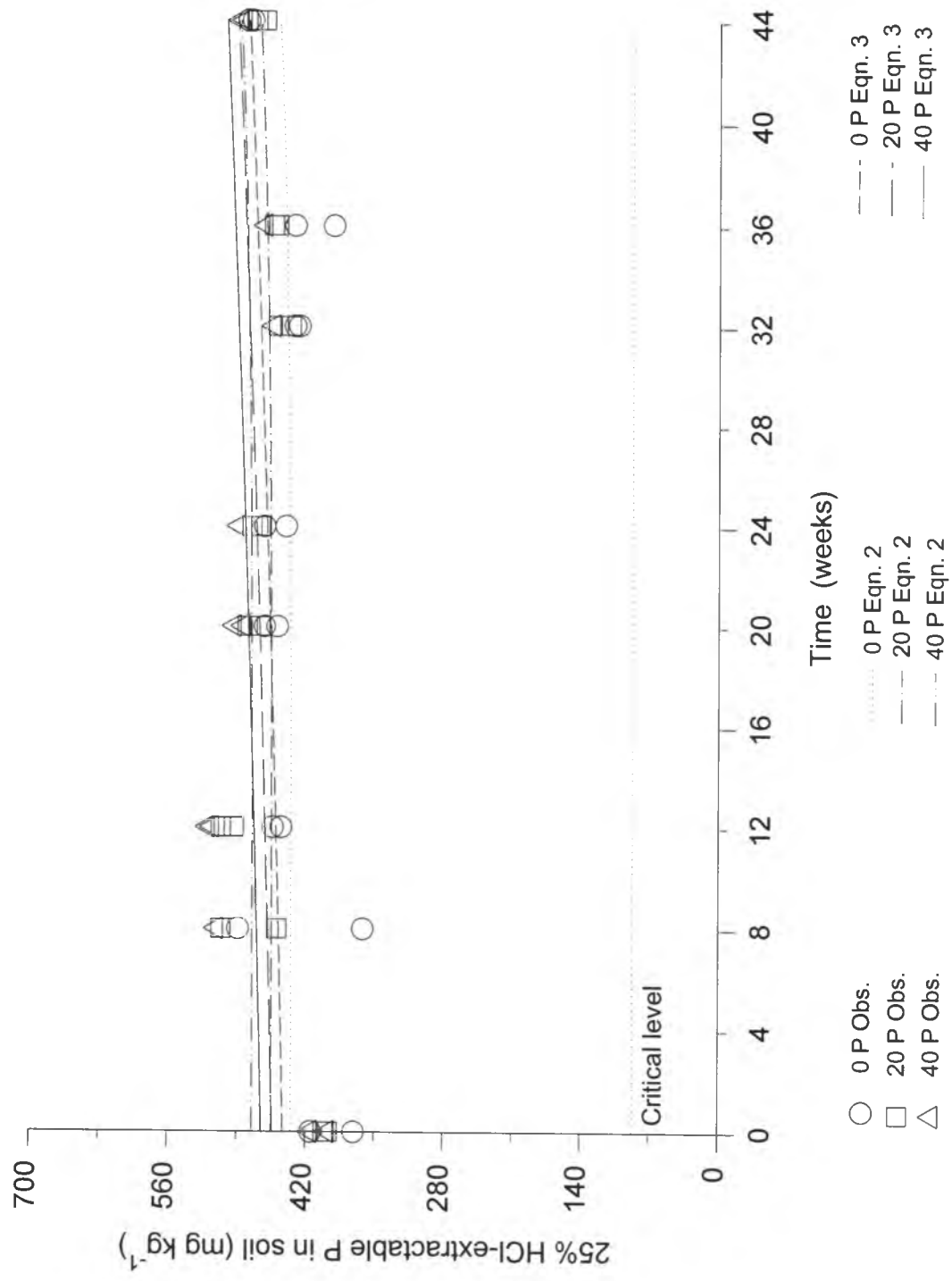


Figure 80. Observed and predicted HCl-extractable P of Cianjur soil without rice crops.

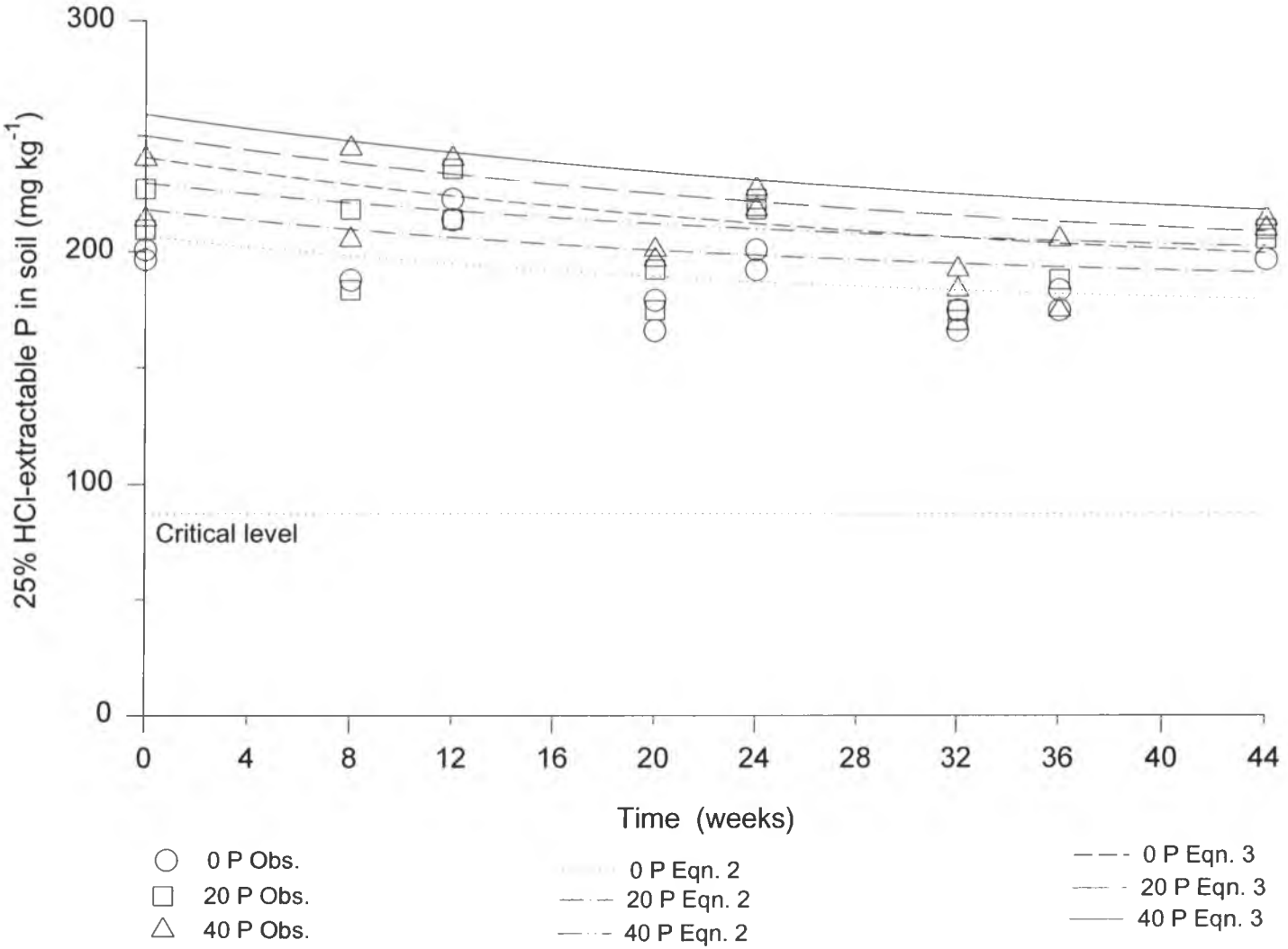


Figure 81. Observed and predicted HCl-extractable P of Purbalingga soil without rice crops.

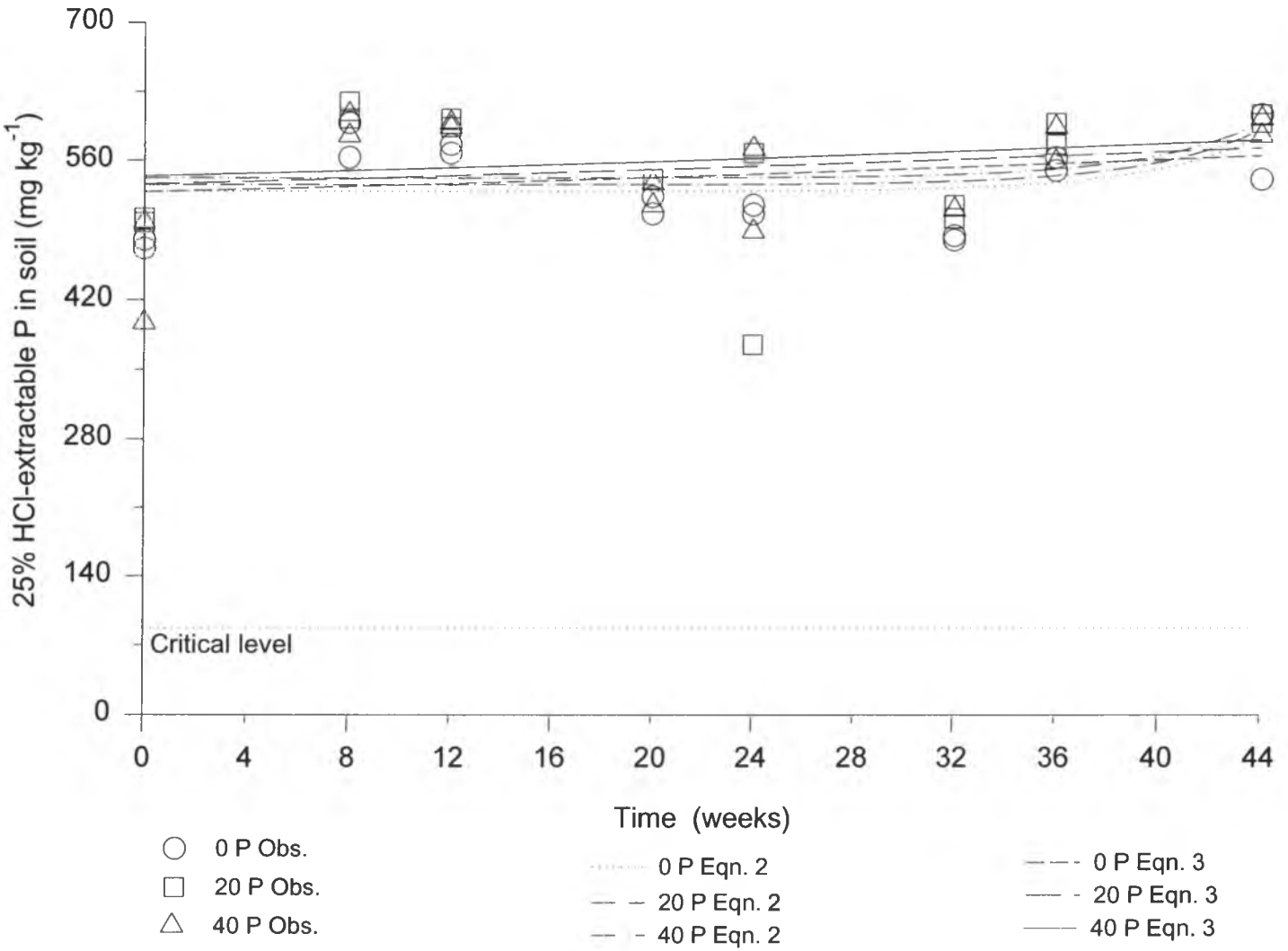


Figure 82. Observed and predicted HCl-extractable P of Purwodadi soil without rice crops.

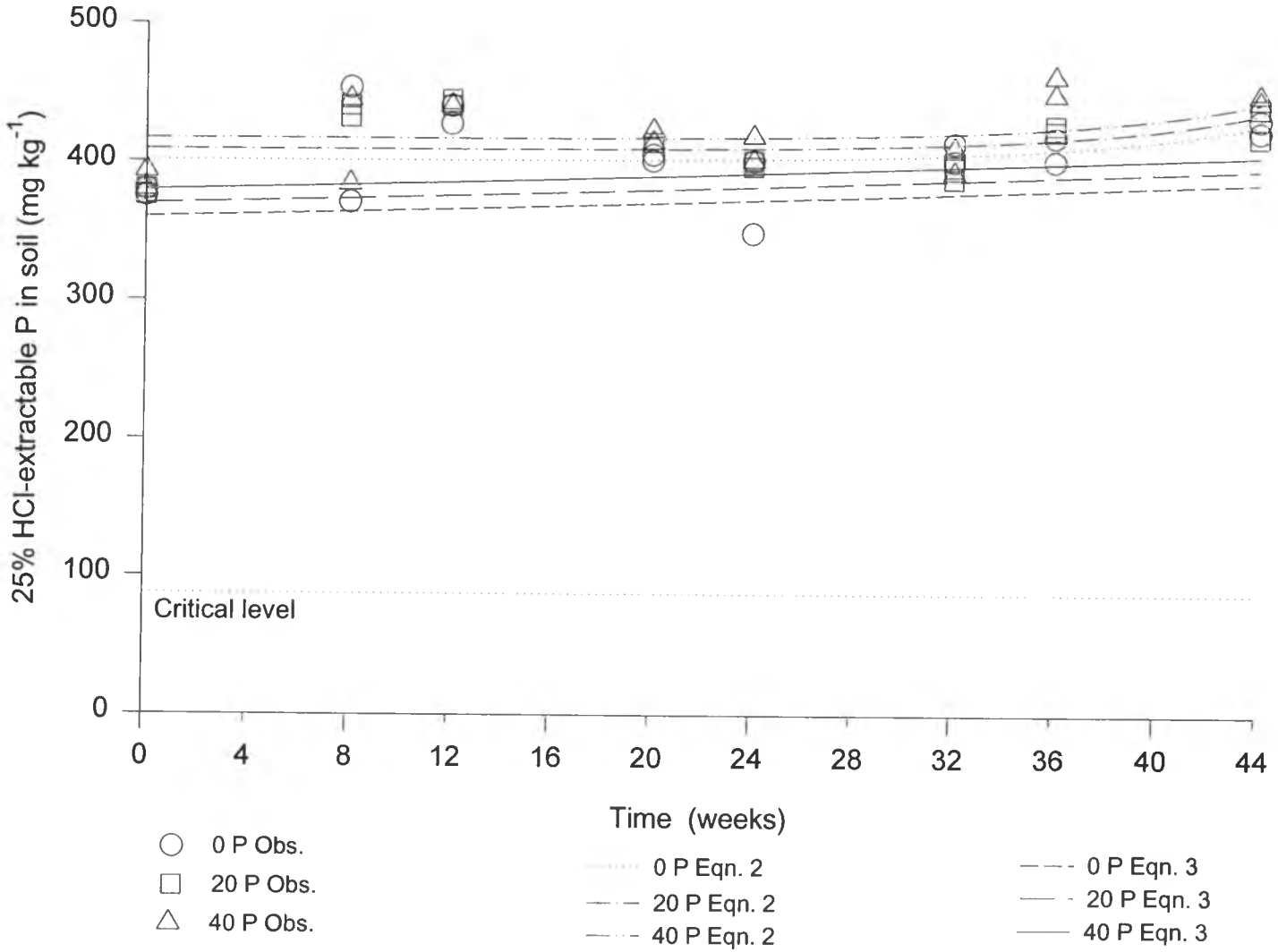


Figure 83. Observed and predicted HCl-extractable P of Madiun soil without rice crops.

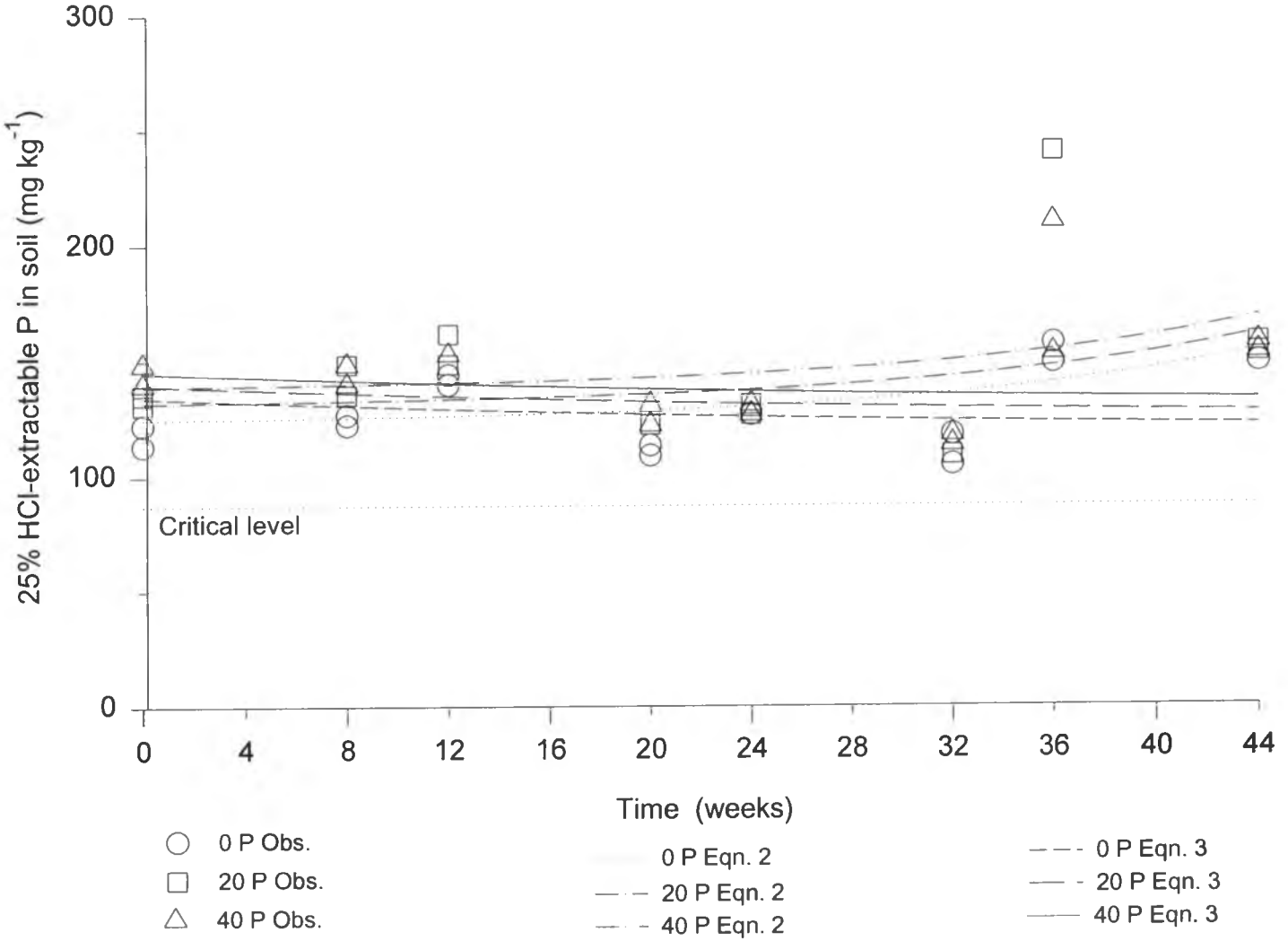


Figure 84. Observed and predicted HCl-extractable P of Mojokerto soil without rice crops.

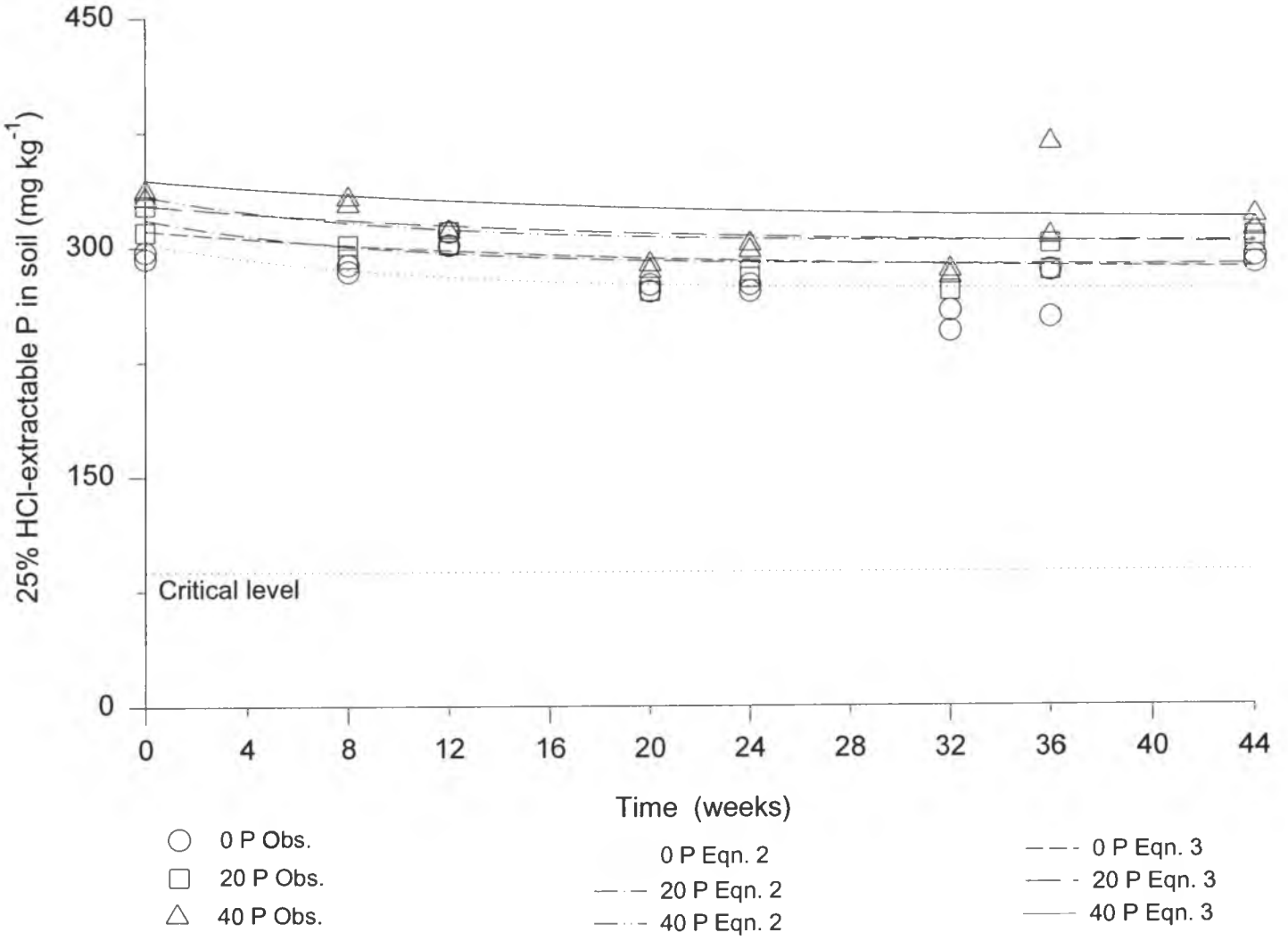


Figure 85. Observed and predicted HCl-extractable P of Jenggawah soil without rice crops.

APPENDIX E. FIGURES 86 TO 91. OBSERVED AND PREDICTED 25% HCl-EXTRACTABLE P WITH RICE

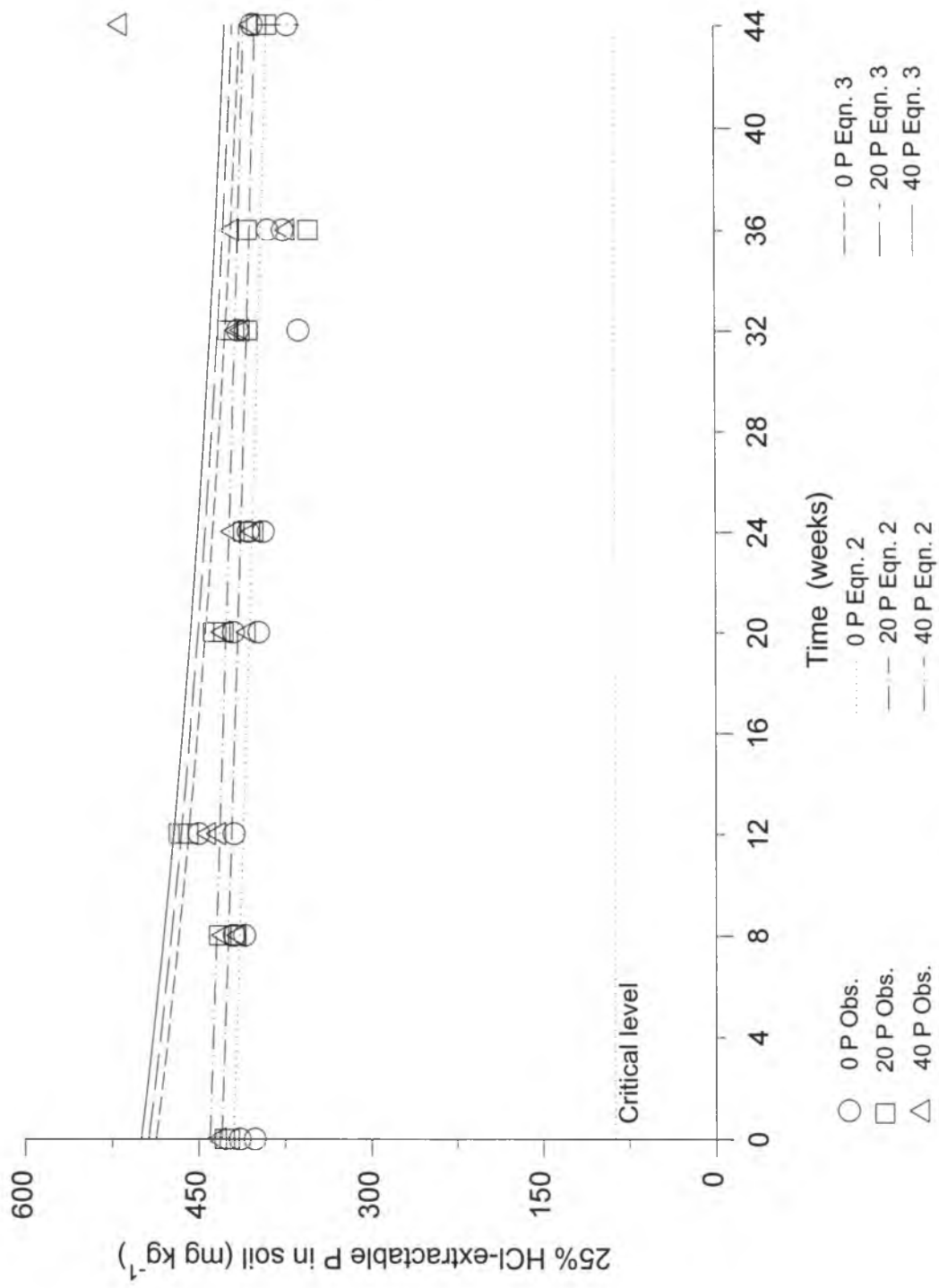


Figure 86. Observed and predicted HCl-extractable P of Cianjur soil with rice crops.

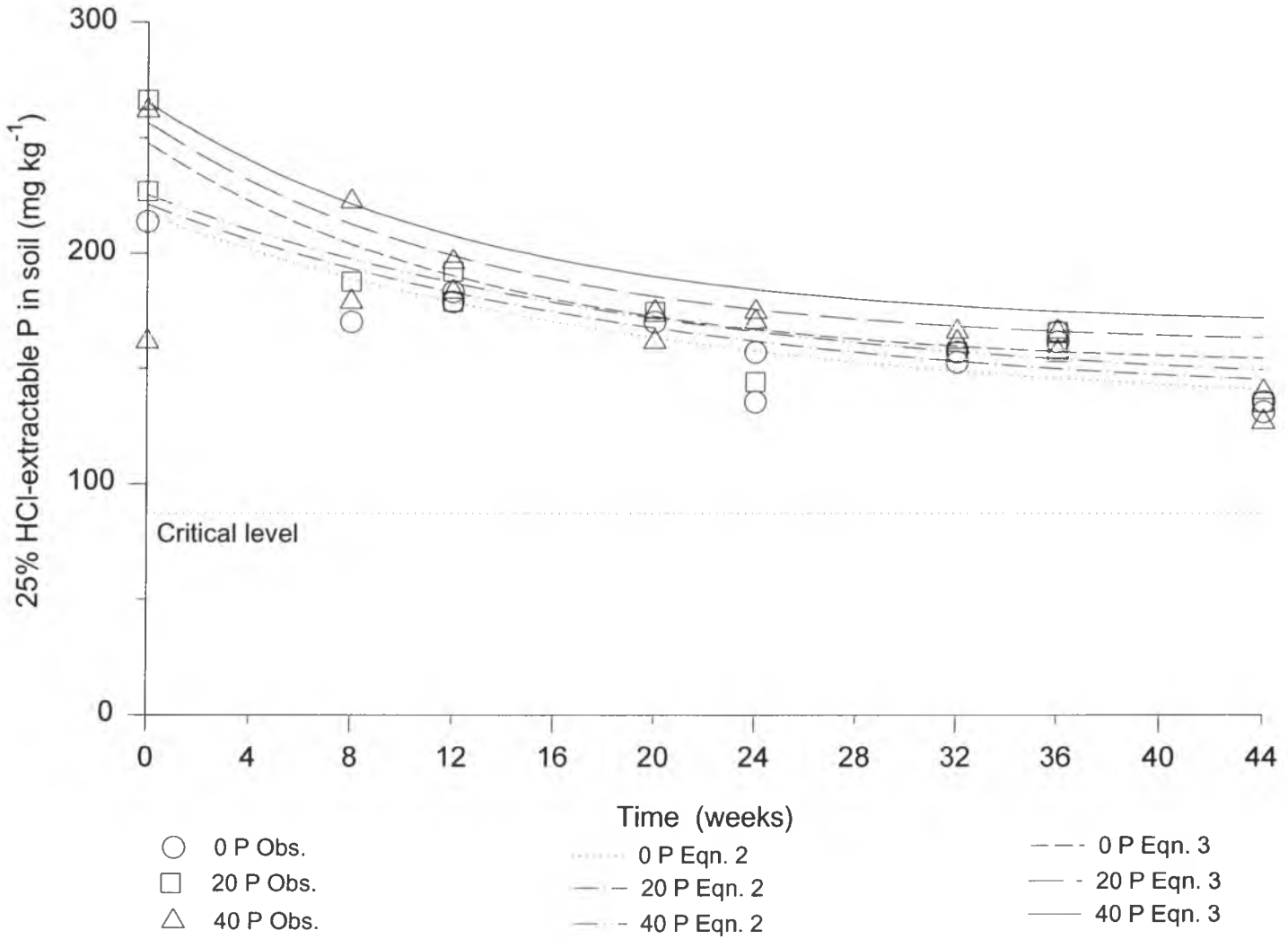


Figure 87. Observed and predicted HCl-extractable P of Purbalingga soil with rice crops.

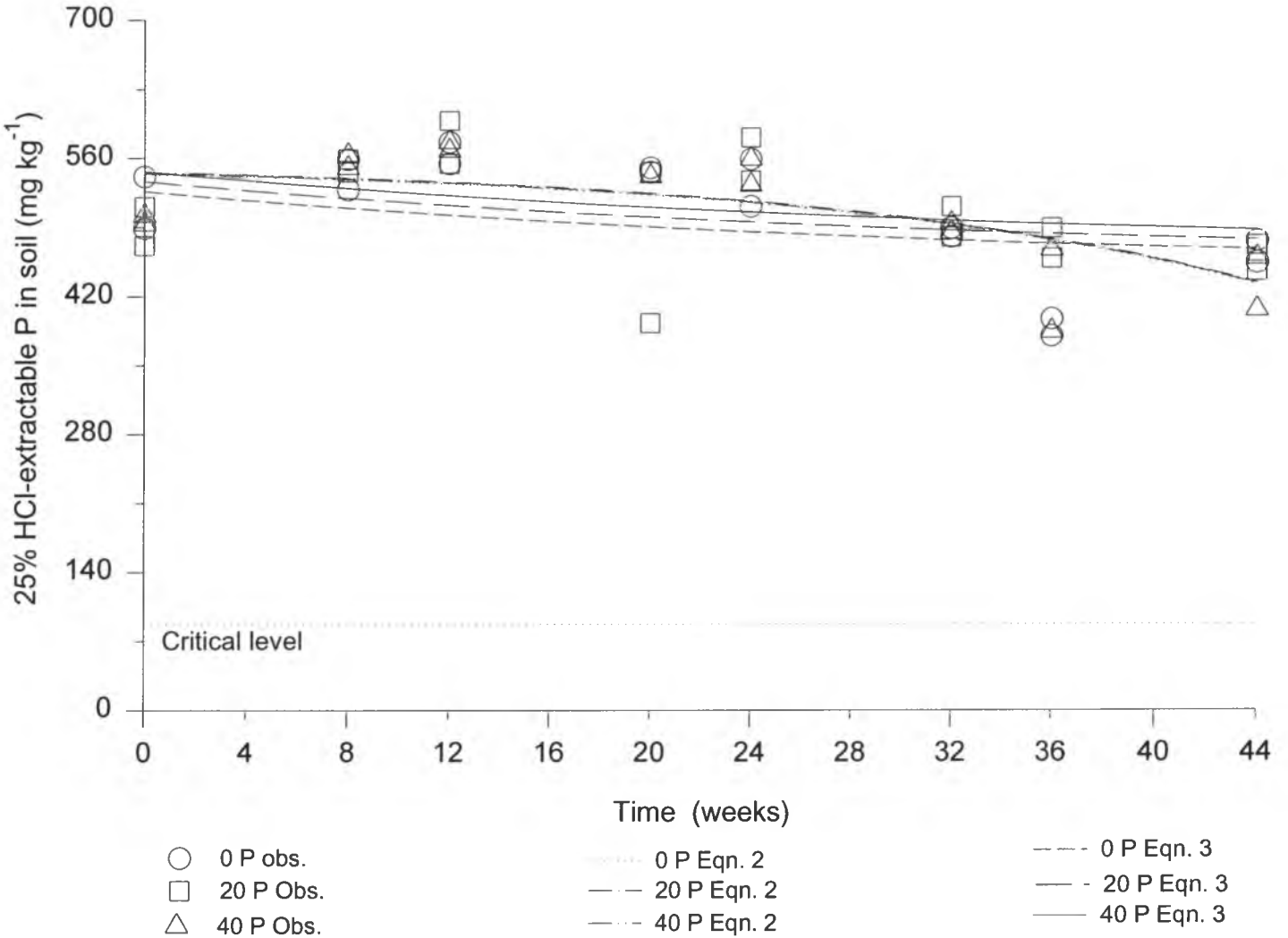


Figure 88. Observed and predicted HCl-extractable P of Purwodadi soil with rice crops.

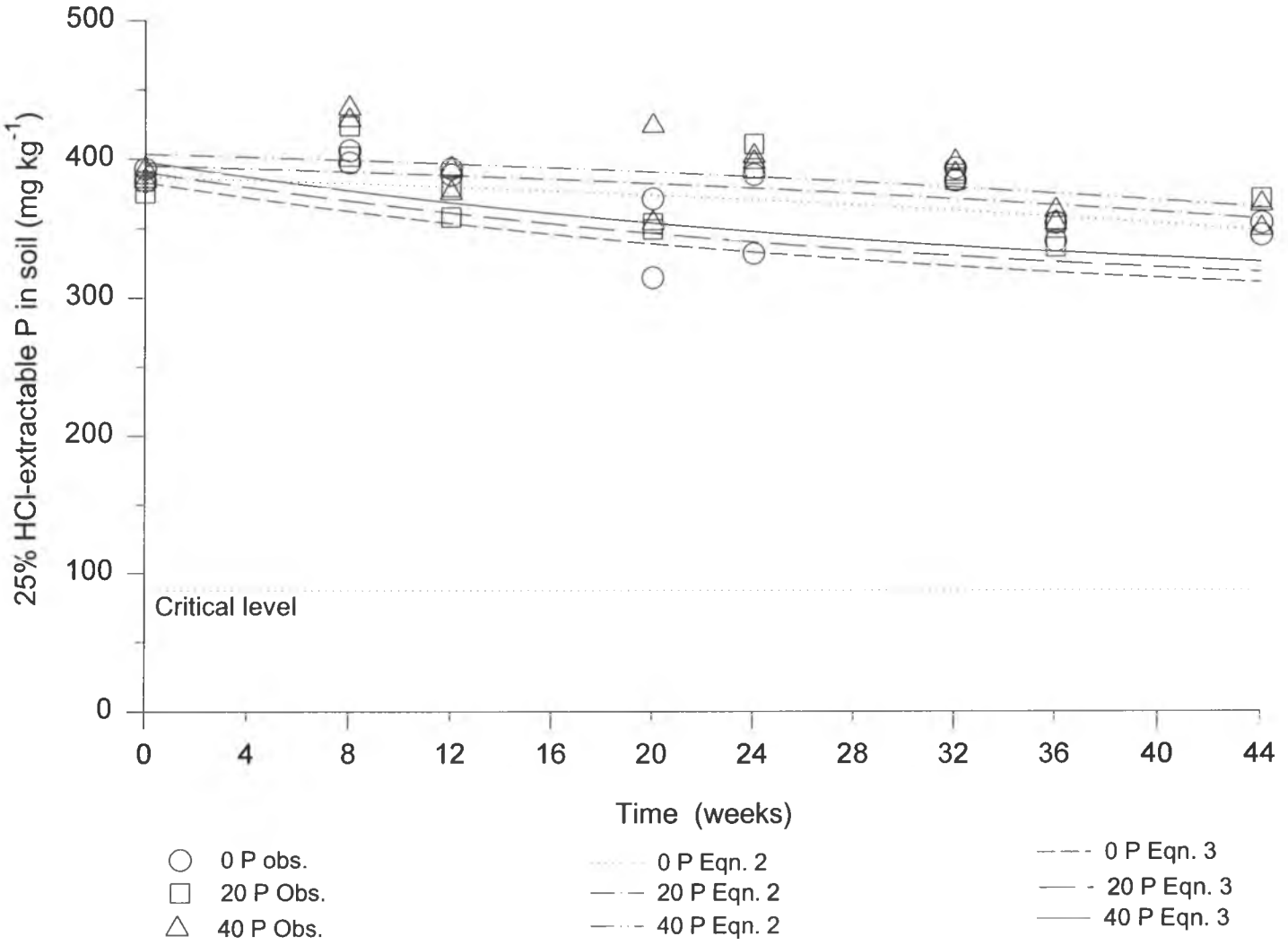


Figure 89. Observed and predicted HCl-extractable P of Madiun soil with rice crops.

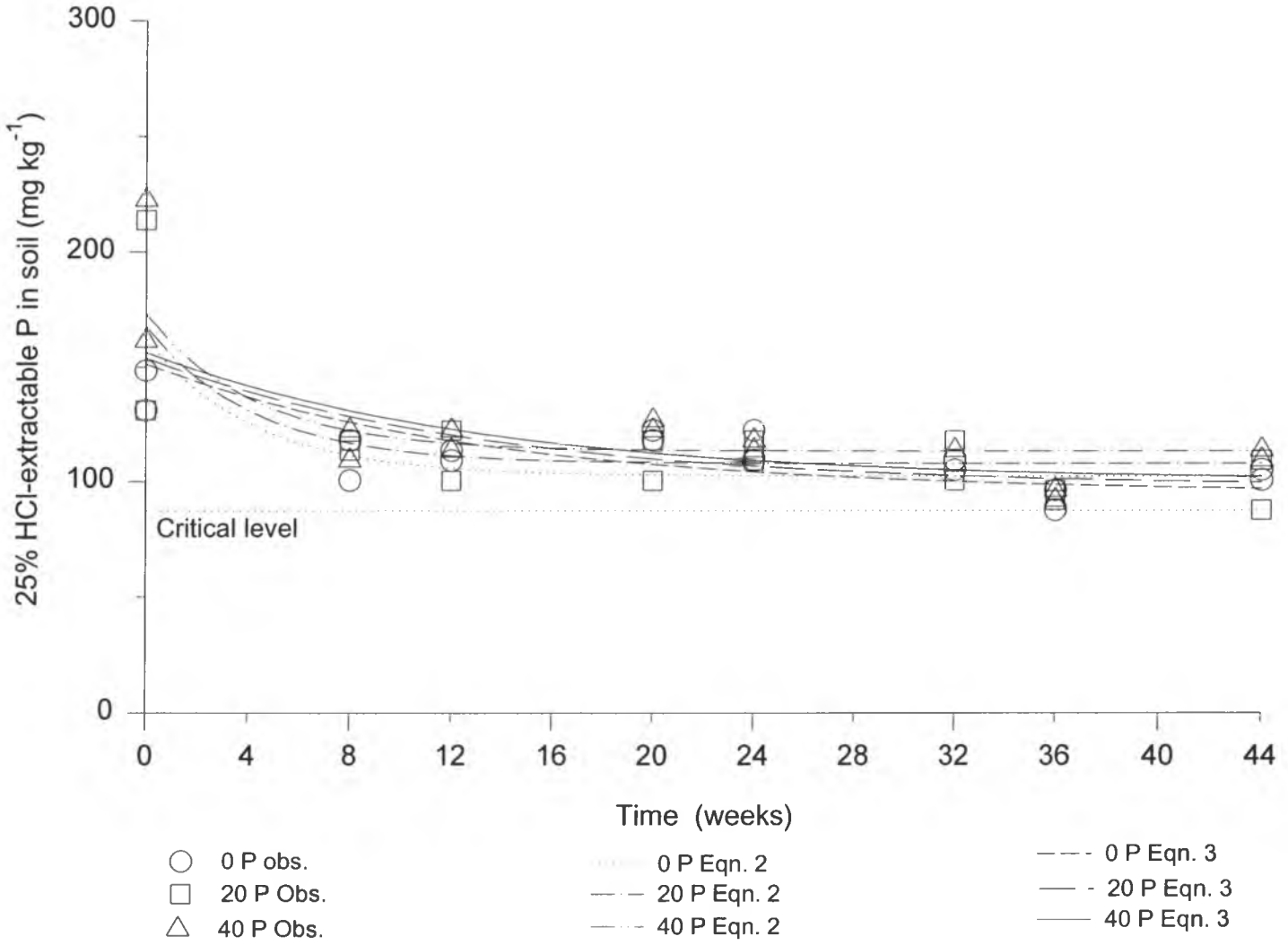


Figure 90. Observed and predicted HCl-extractable P of Mojokerto soil with rice crops.

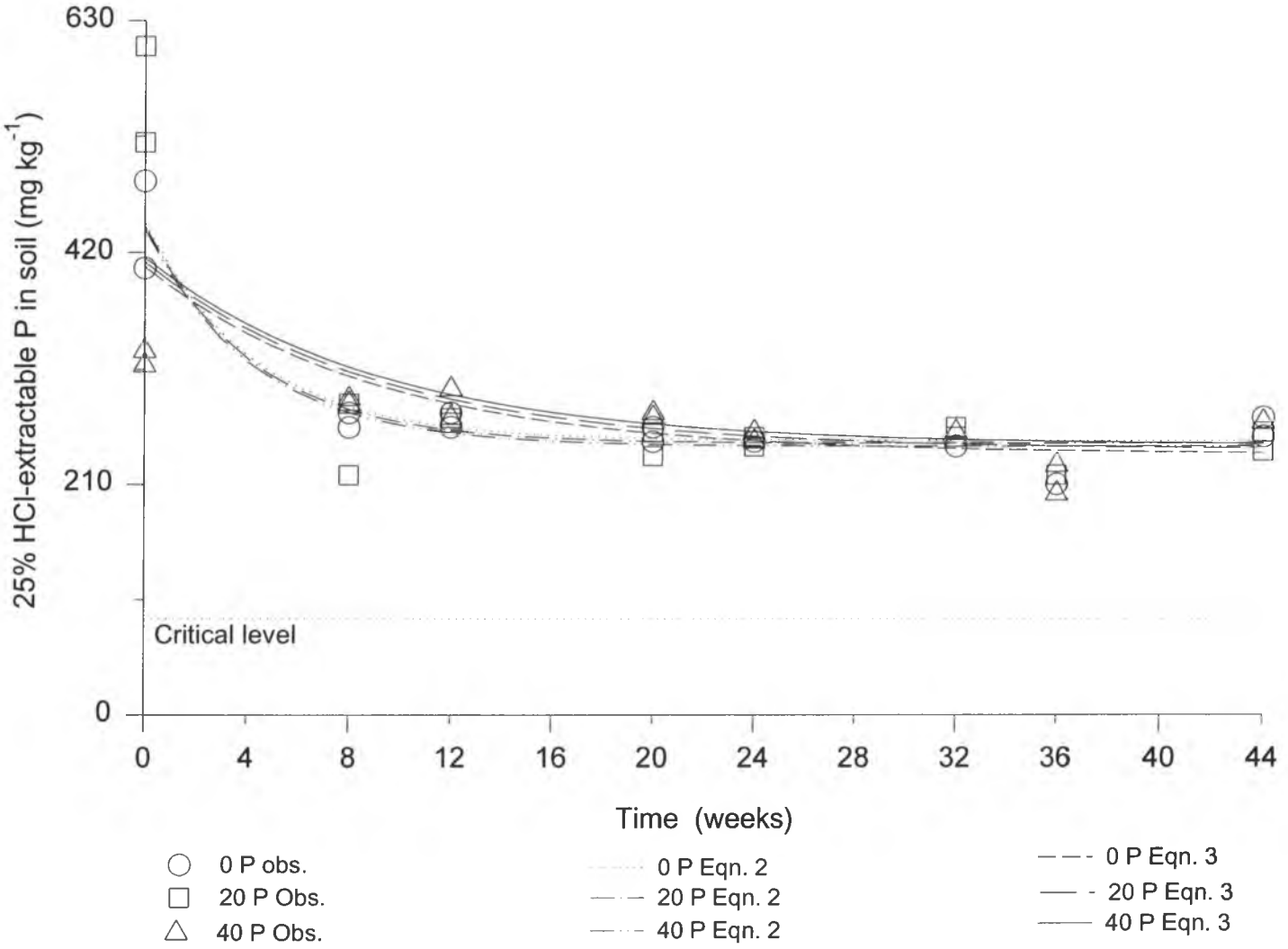


Figure 91. Observed and predicted HCl-extractable P of Jenggawah soil with rice crops.

APPENDIX F. FIGURES 92 TO 97. CALCULATED AND PREDICTED TOTAL DESORPTION OF 0.5*M* $NaHCO_3$-RESIDUAL P

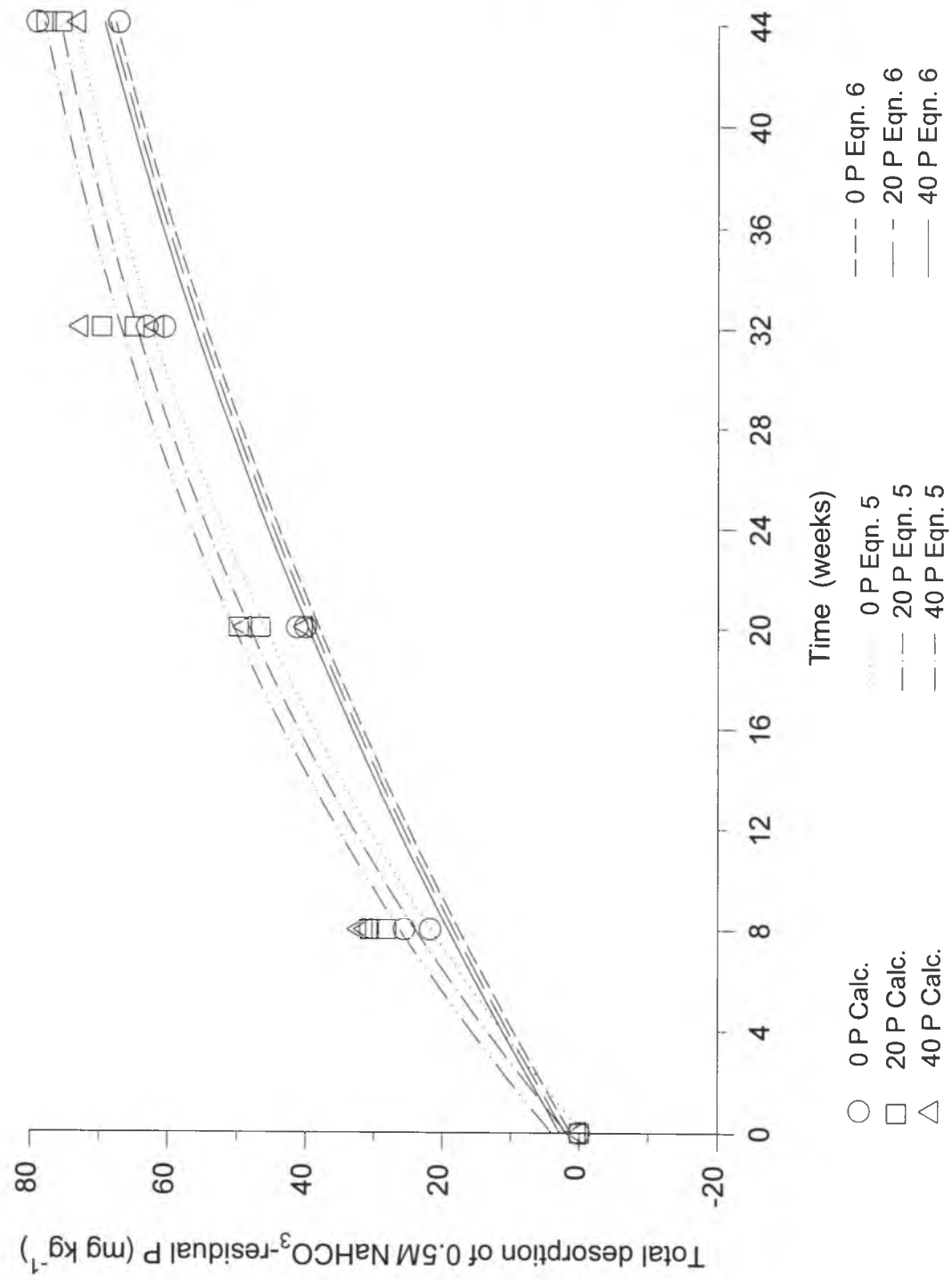


Figure 92. Calculated and predicted total desorption of 0.5*M* $NaHCO_3$-residual P of Cianjur soil.

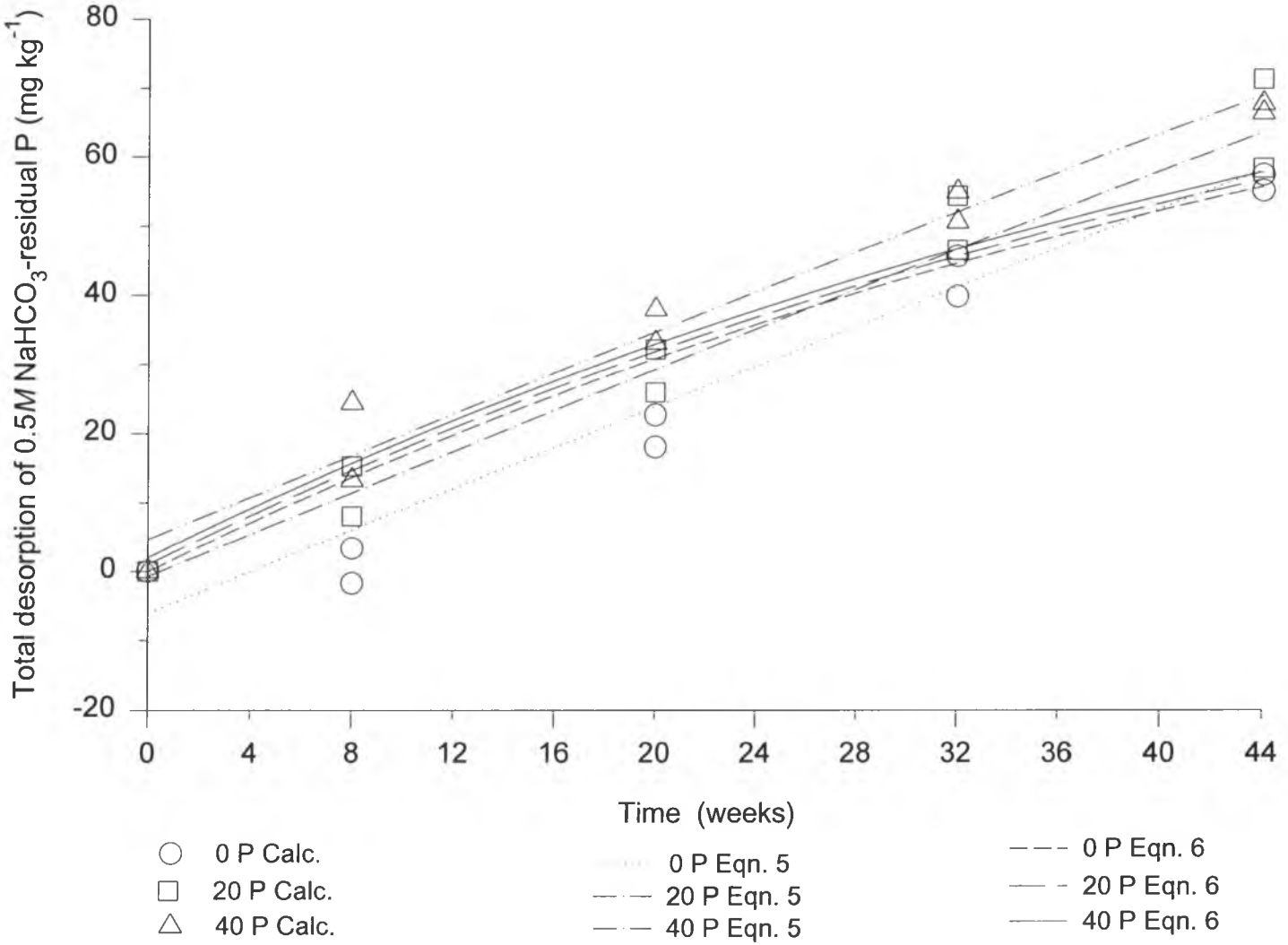


Figure 93. Calculated and predicted total desorption of 0.5*M* $NaHCO_3$-residual P of Purbalingga soil.

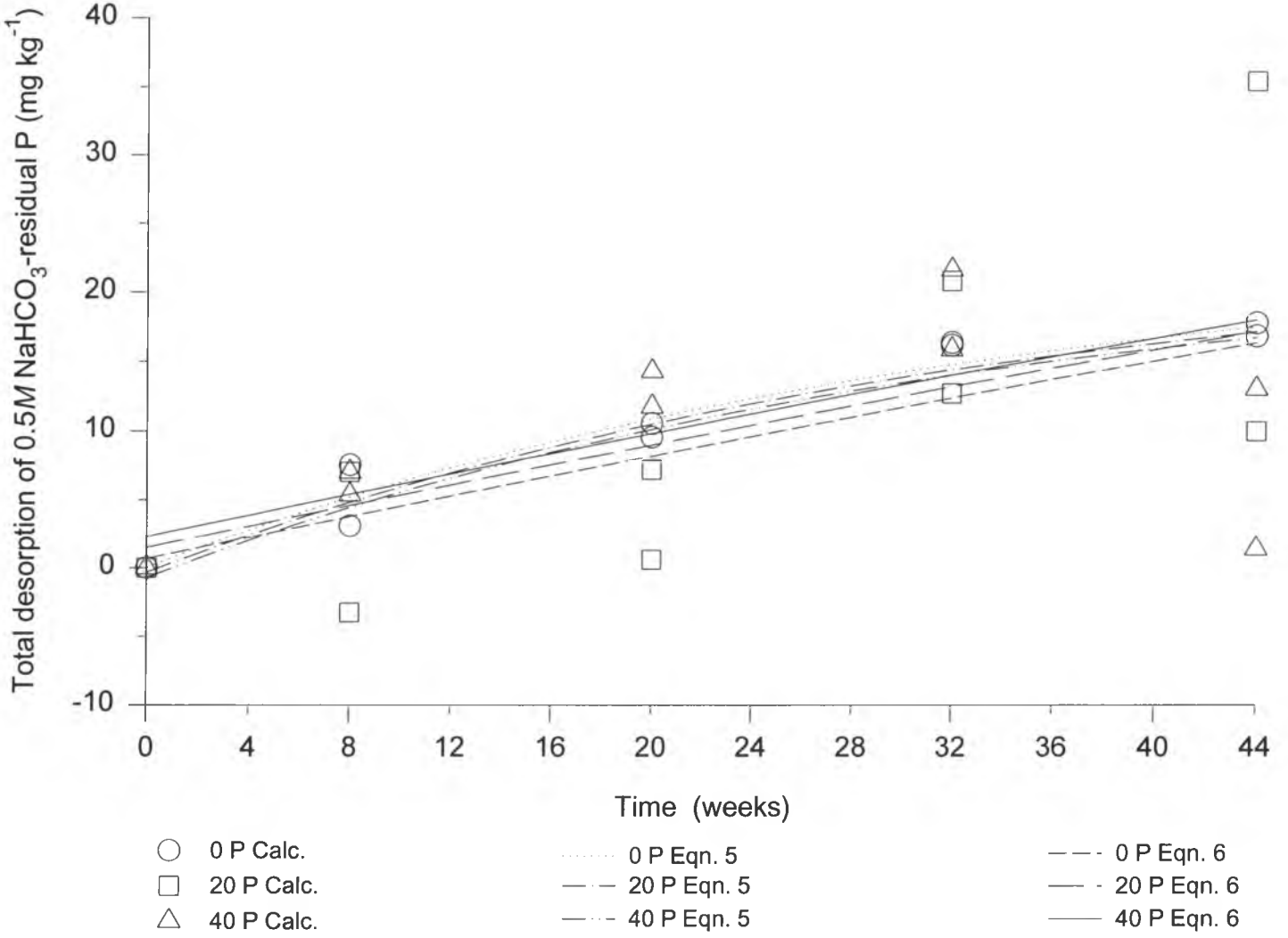


Figure 94. Calculated and predicted total desorption of 0.5*M* $NaHCO_3$-residual P of Purwodadi soil.

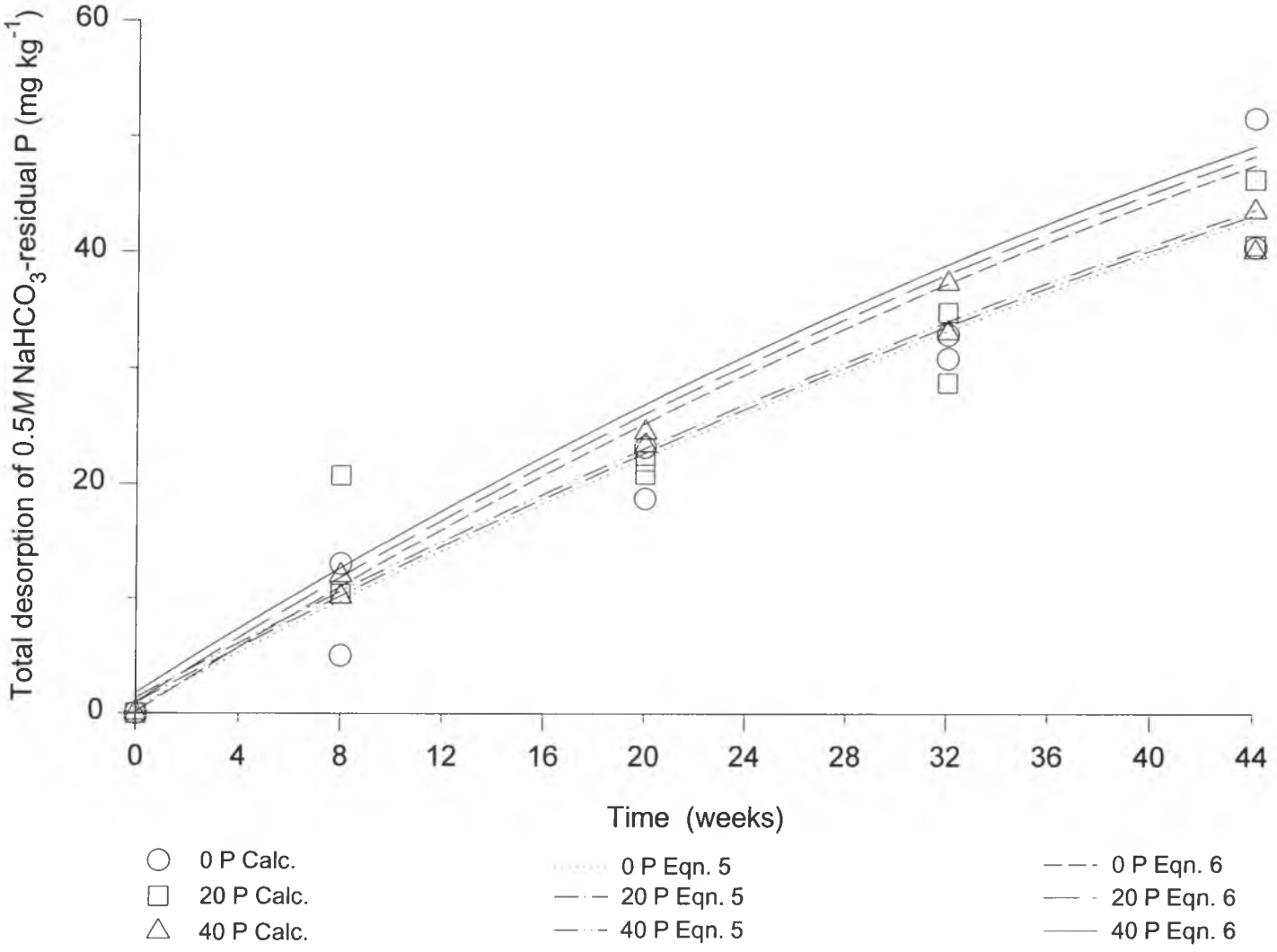


Figure 95. Calculated and predicted total desorption of 0.5*M* $NaHCO_3$-residual P of Madiun soil.

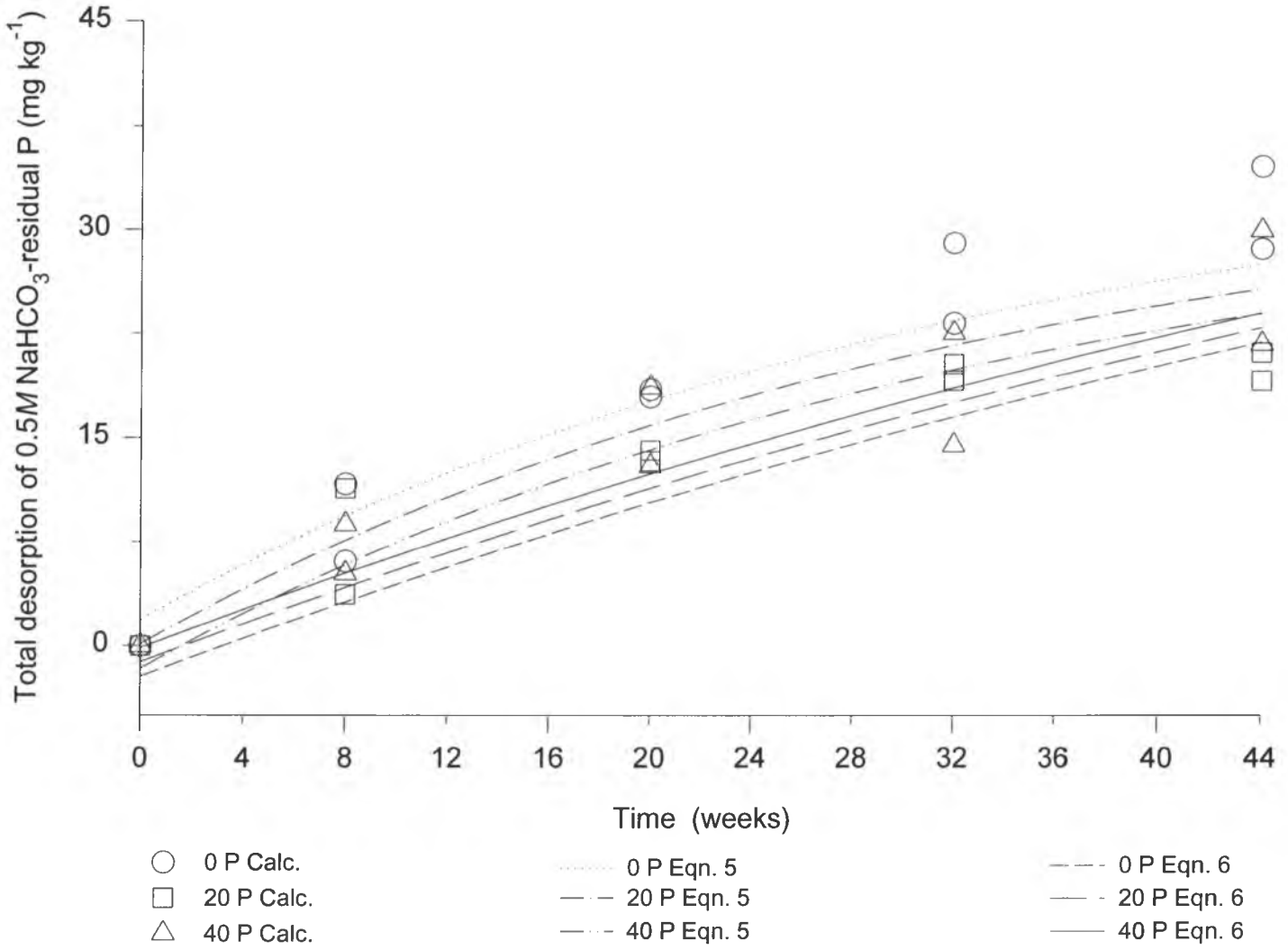


Figure 96. Calculated and predicted total desorption of $0.5M$ $NaHCO_3$-residual P of Mojokerto soil.

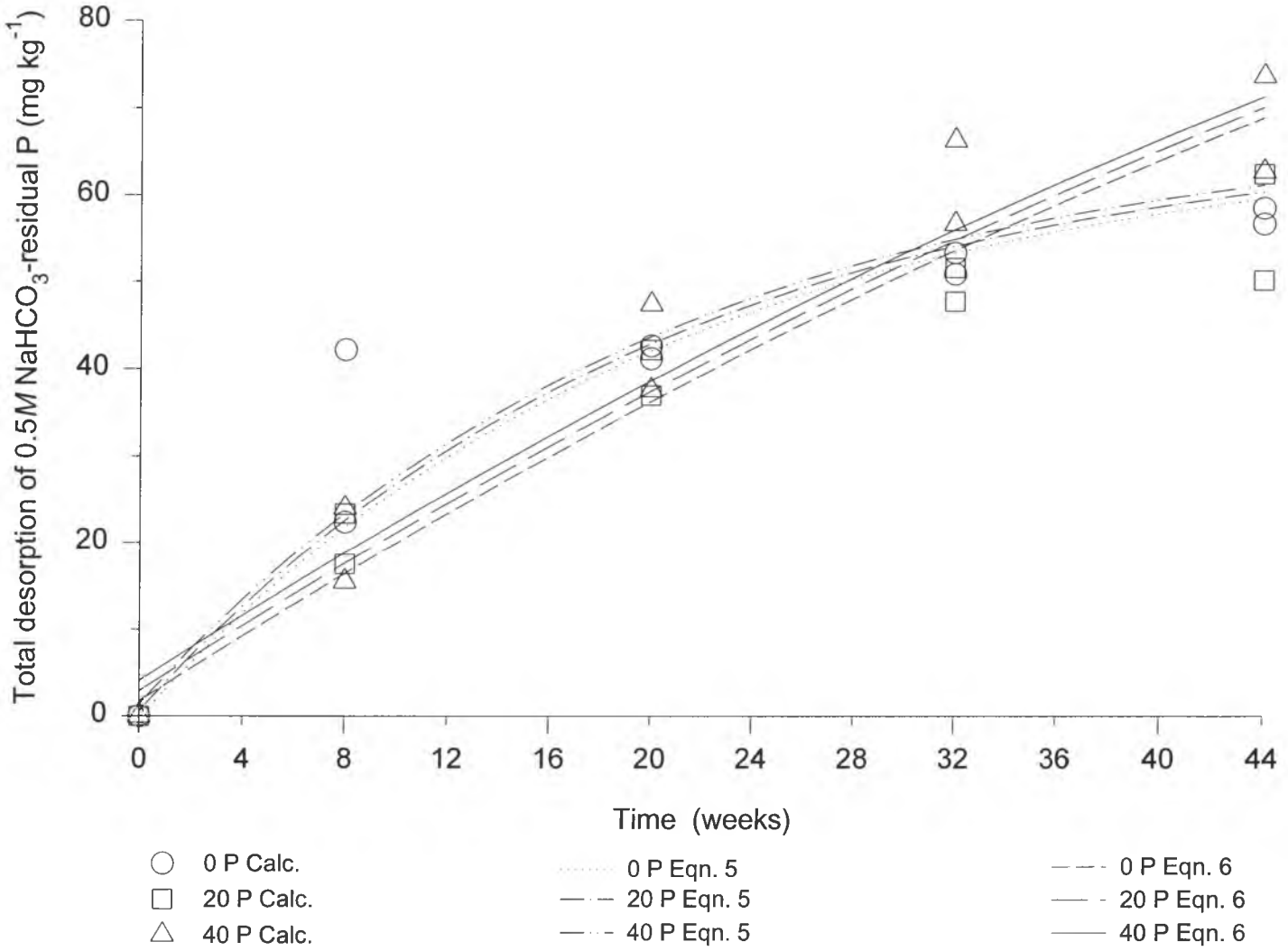


Figure 97. Calculated and predicted total desorption of 0.5*M* $NaHCO_3$-residual P of Jenggawah soil.

APPENDIX G. FIGURES 98 TO 103. CALCULATED AND PREDICTED TOTAL DESORPTION OF 25% HCl-RESIDUAL P

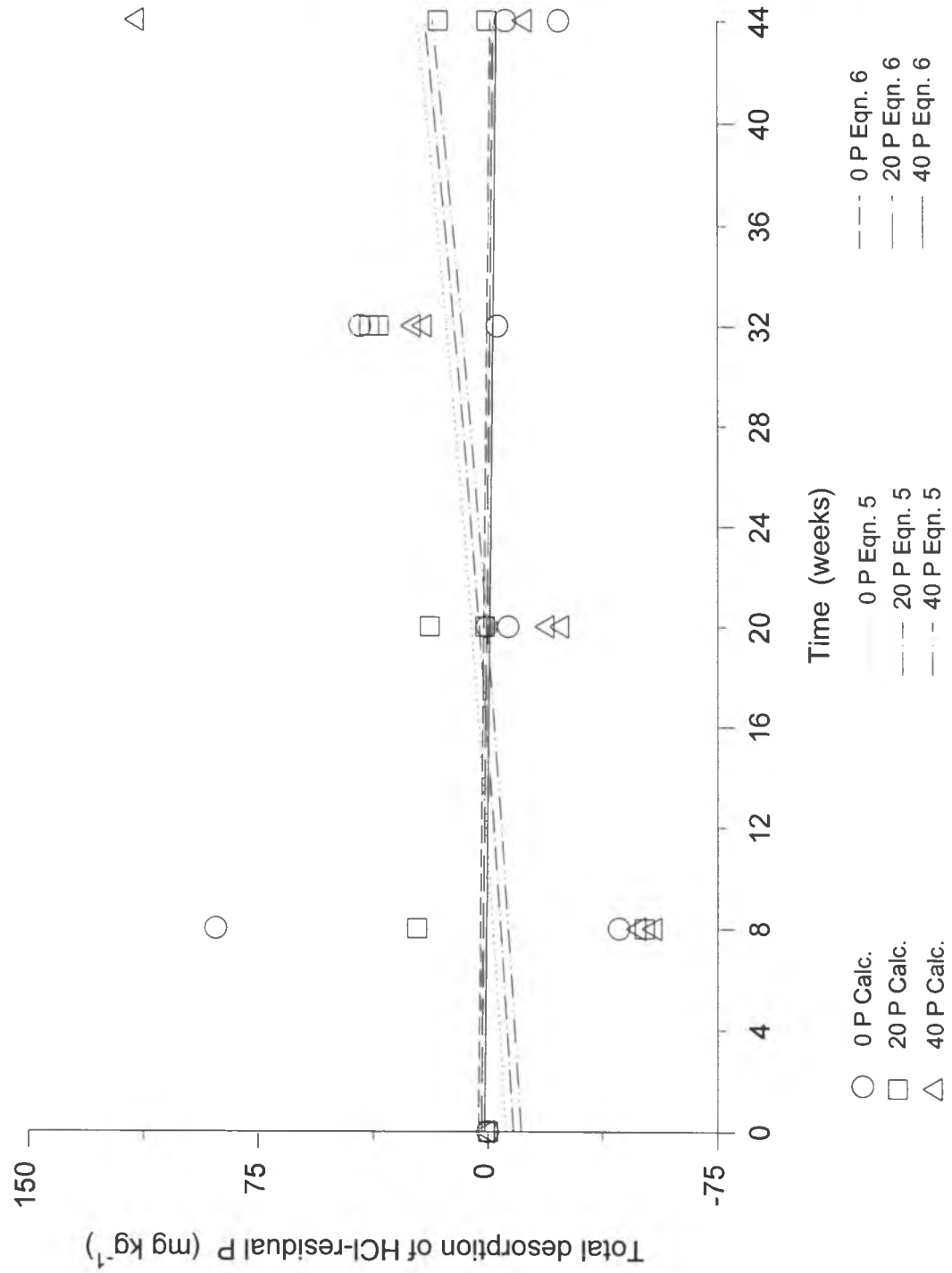


Figure 98. Calculated and predicted total desorption of HCl-residual P of Cianjur soil.

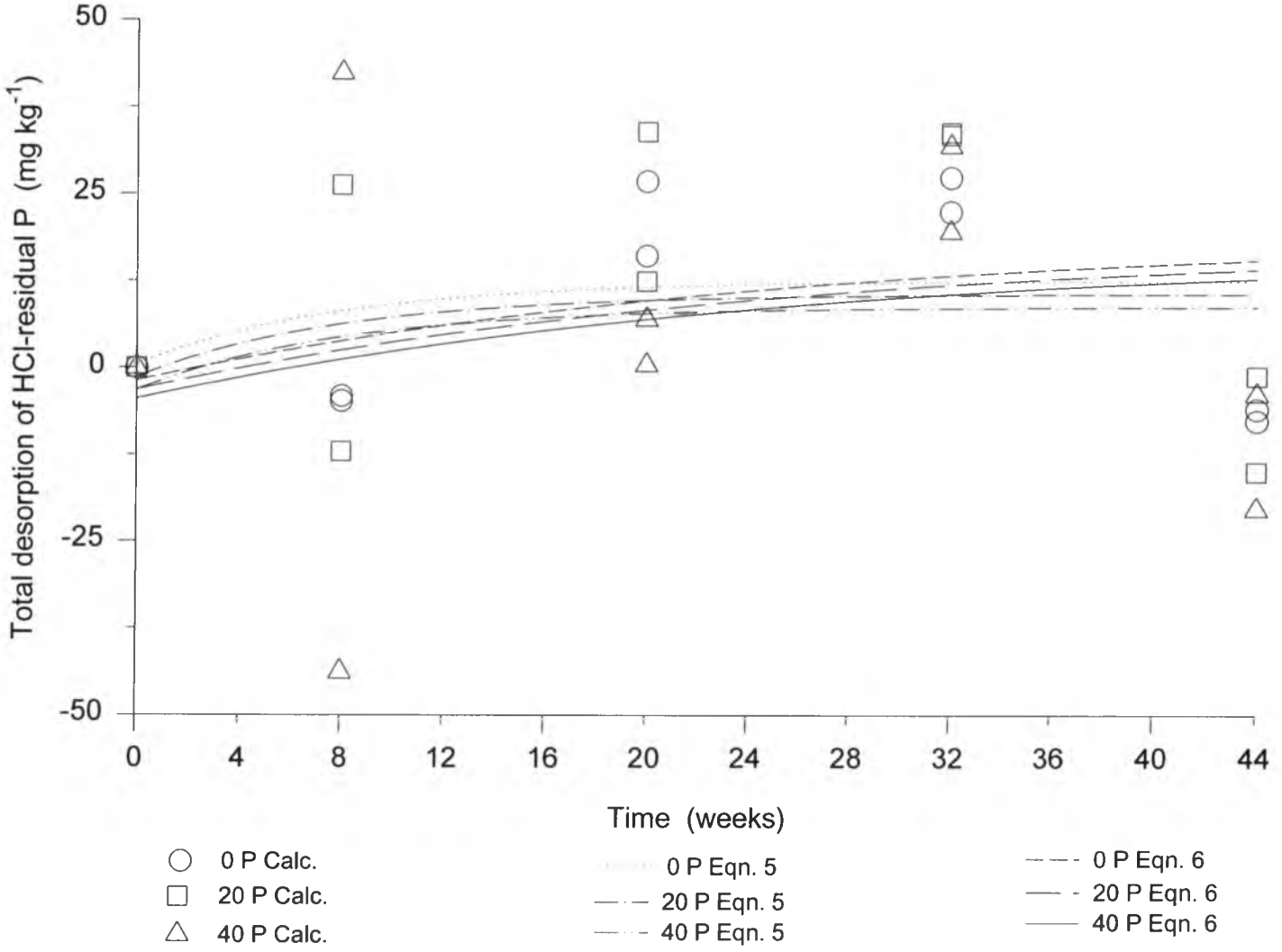


Figure 99. Calculated and predicted total desorption of HCl-residual P of Purbalingga soil.

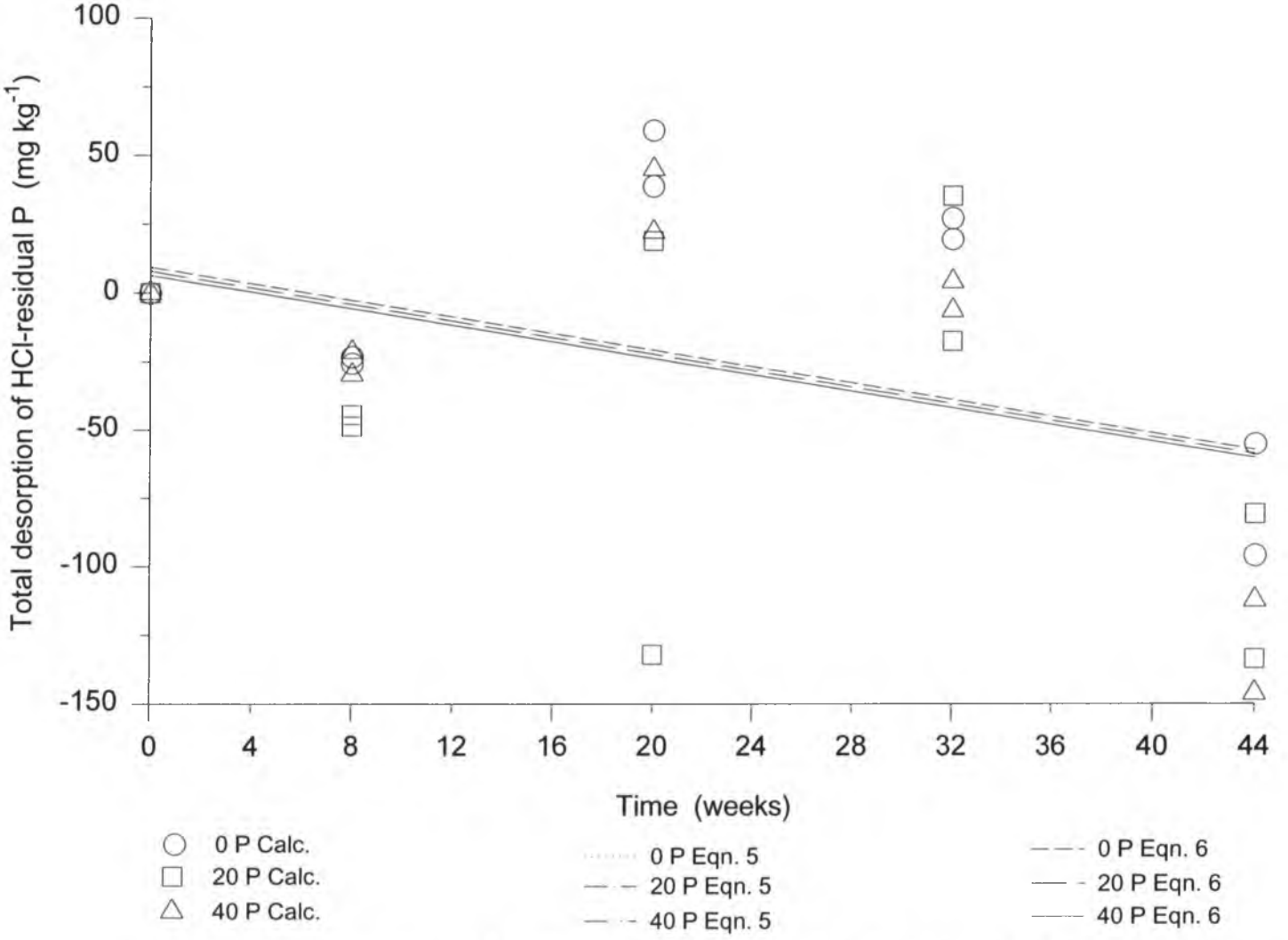


Figure 100. Calculated and predicted total desorption of HCl-residual P of Purwodadi soil.

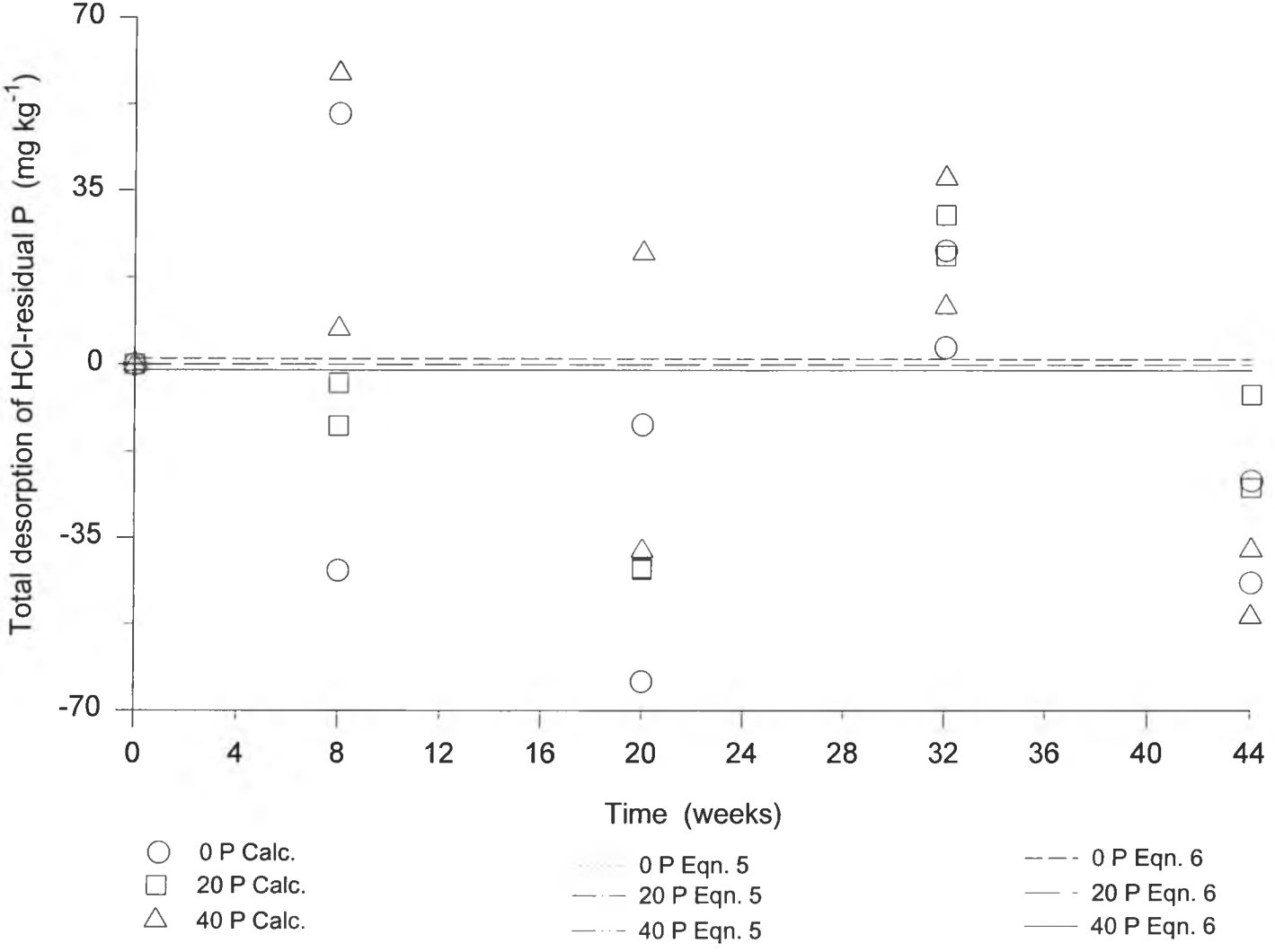


Figure 101. Calculated and predicted total desorption of HCl-residual P of Madiun soil.

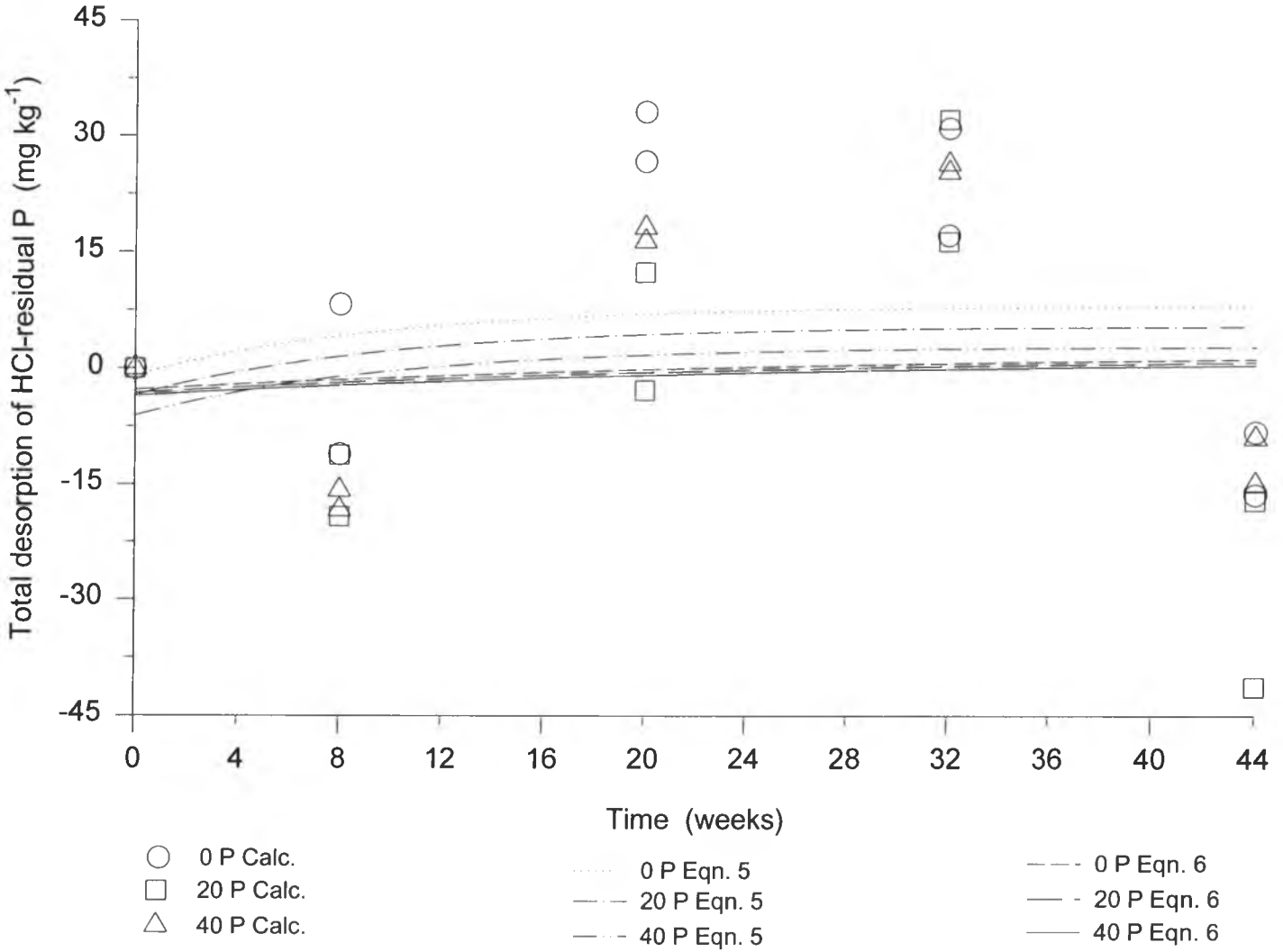


Figure 102. Calculated and predicted total desorption of HCl-residual P of Mojokerto soil.

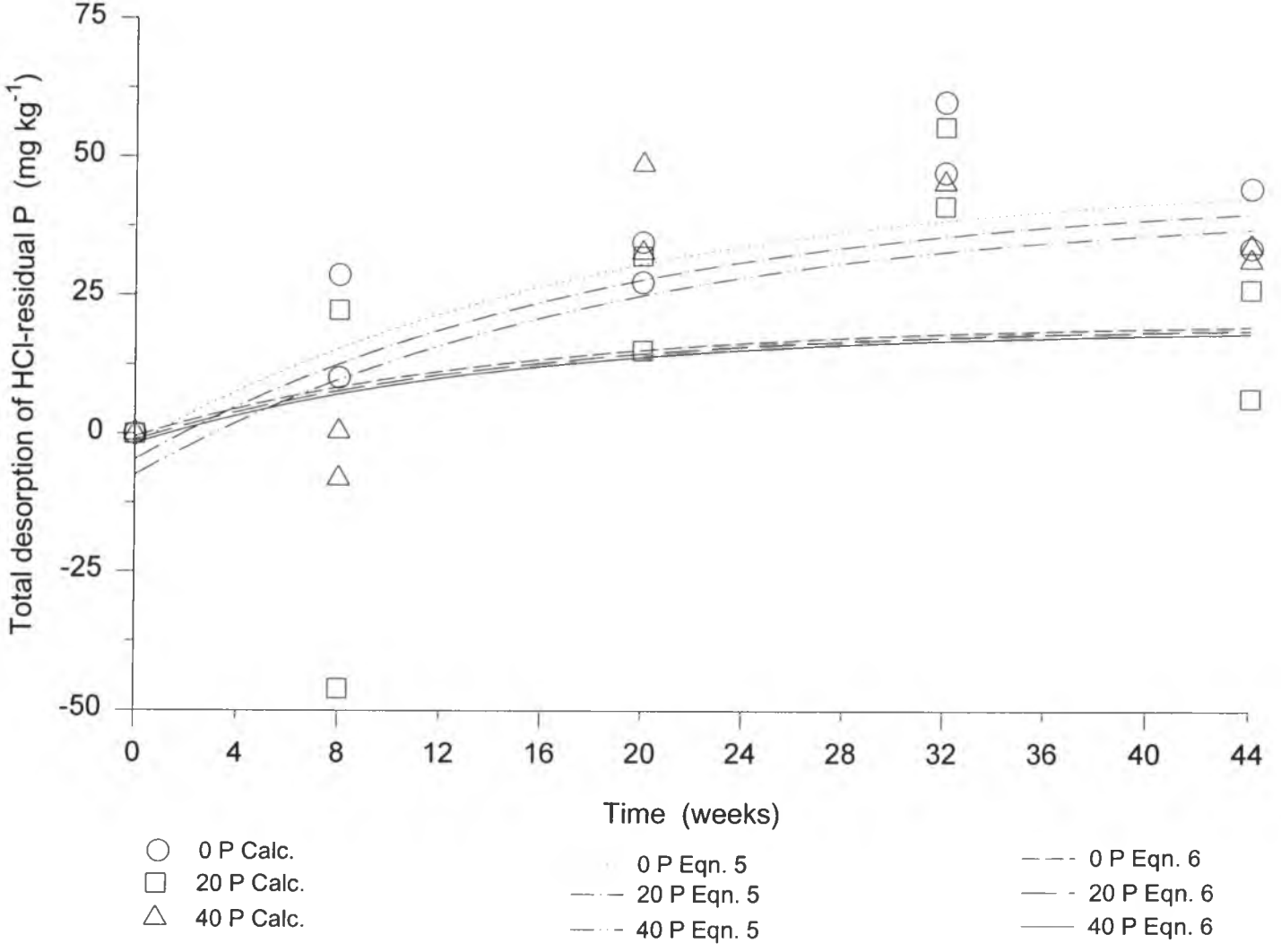
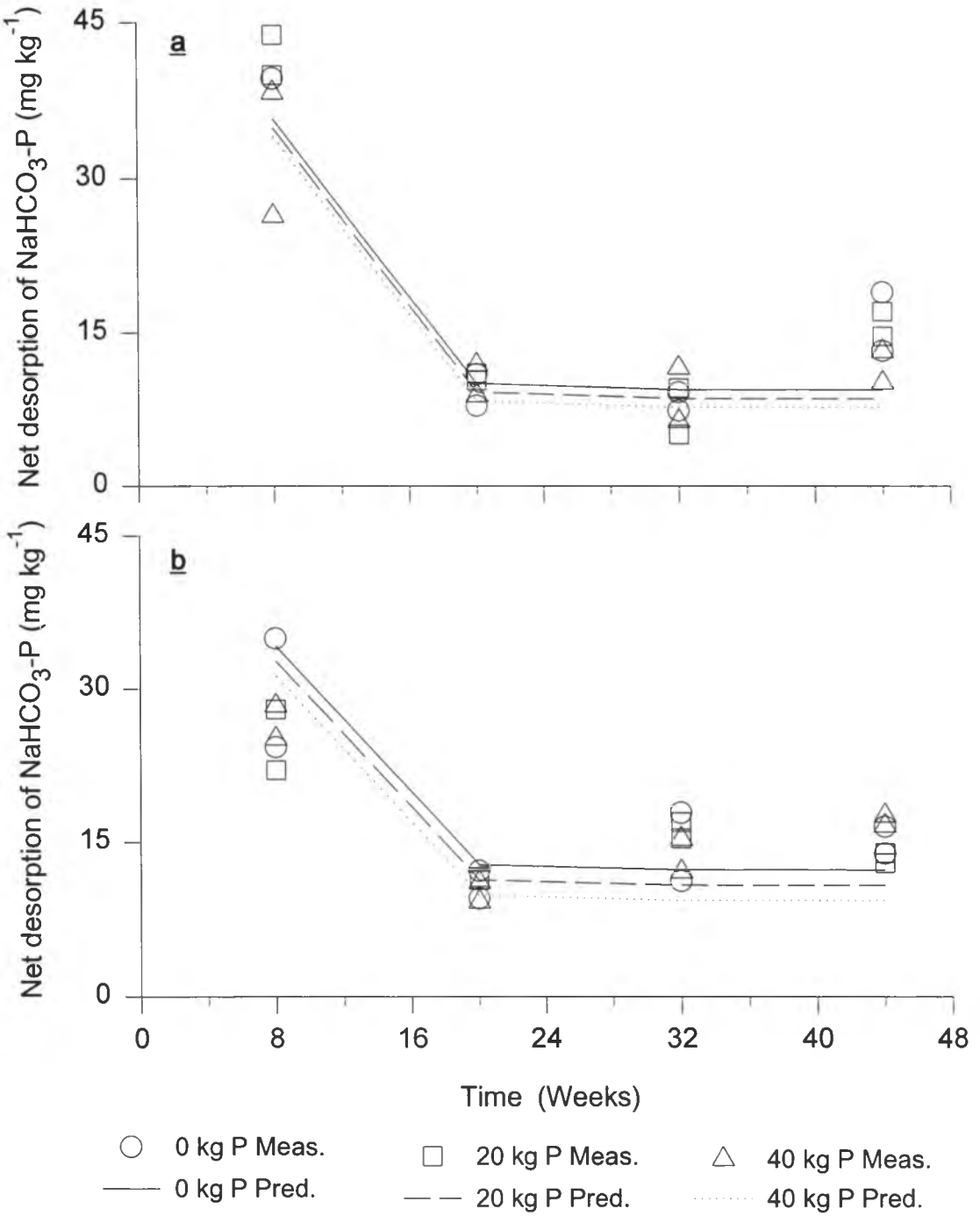
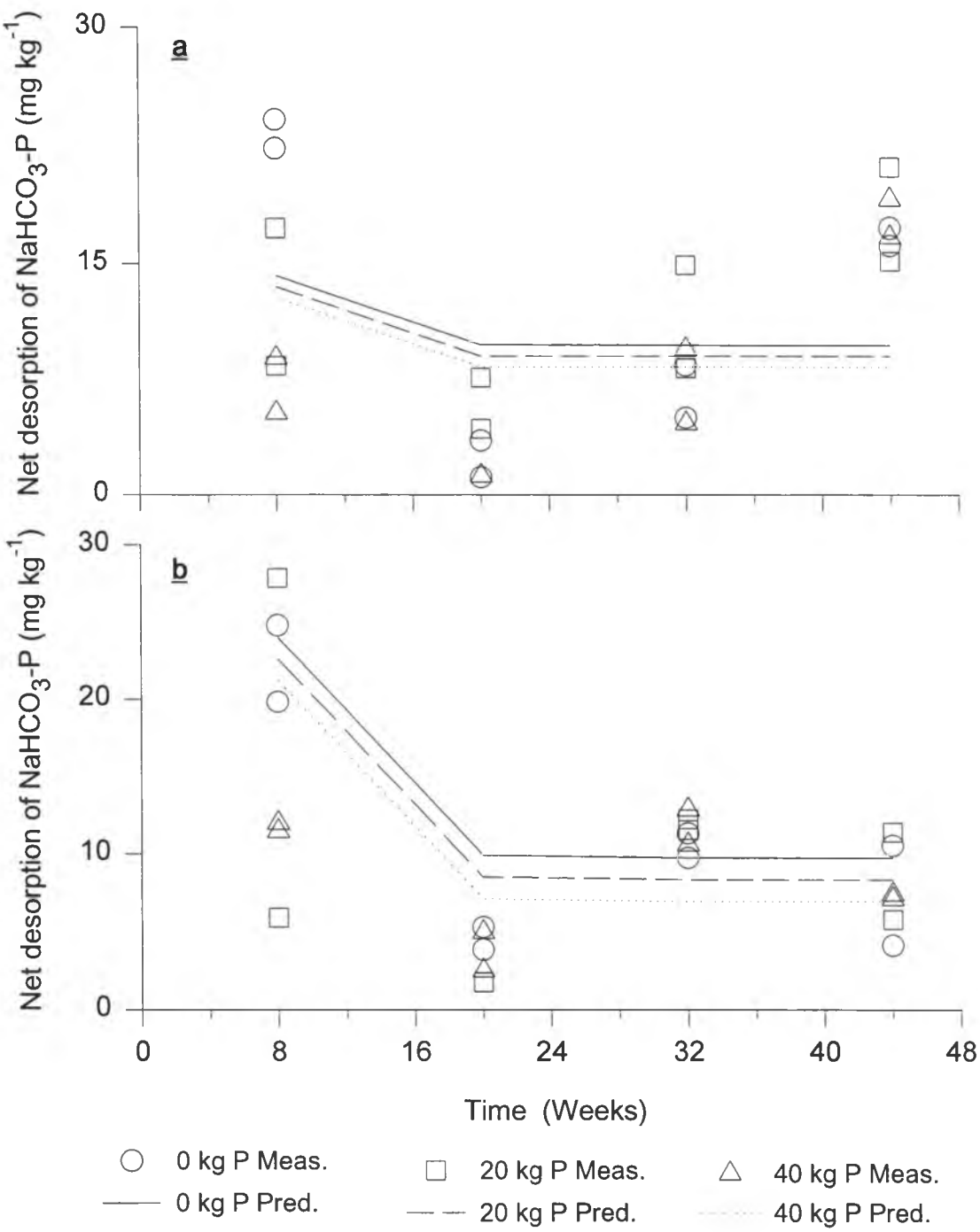


Figure 103. Calculated and predicted total desorption of HCl-residual P of Jenggawah soil.

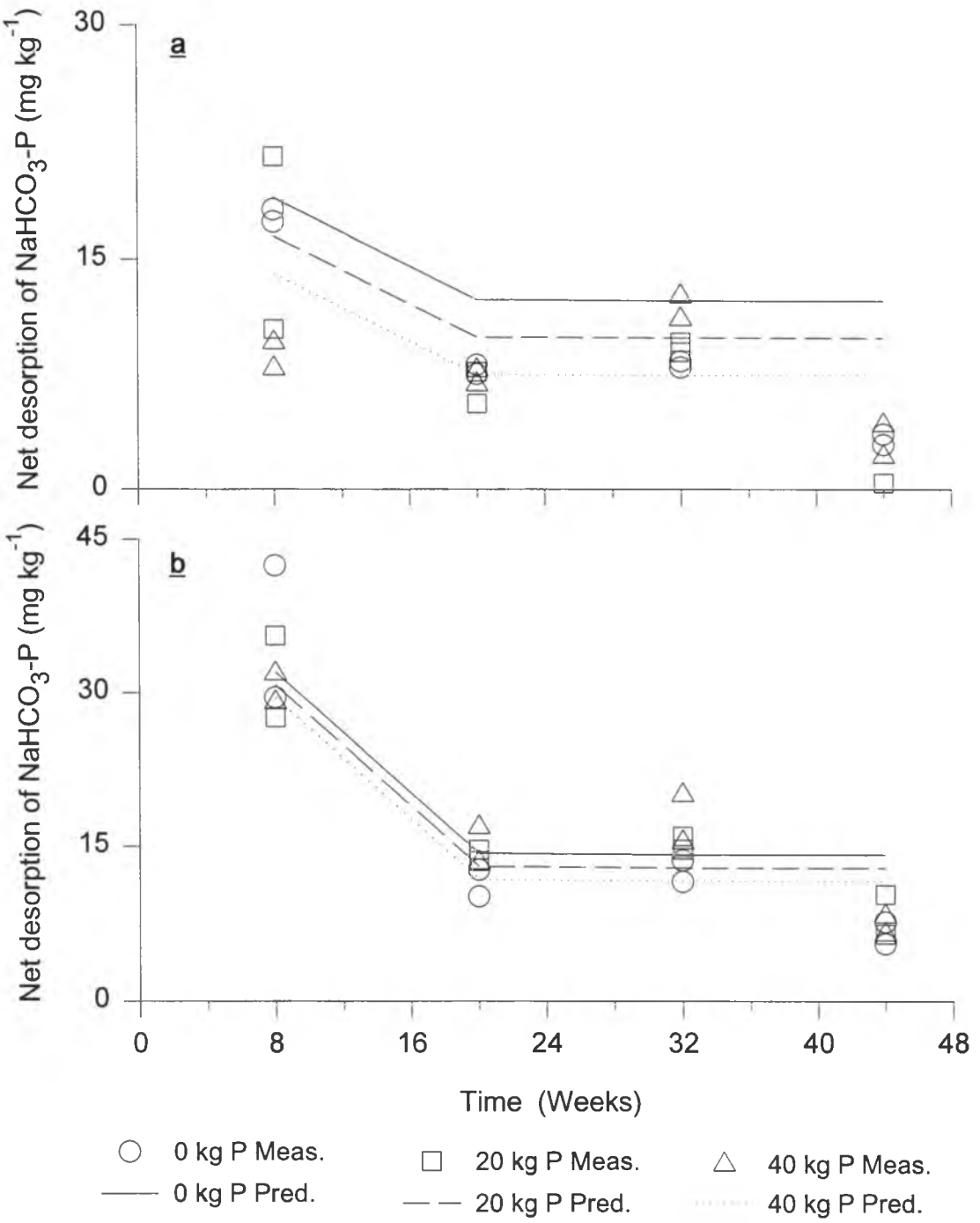
APPENDIX H. FIGURES 104a & b TO 106a & b. CALCULATED AND PREDICTED NET DESORPTION OF 0.5*M* $NaHCO_3$-P



Figures 104a & b. Calculated and predicted net desorption of $NaHCO_3$-P of Cianjur (a), and Purbalingga (b) soils.

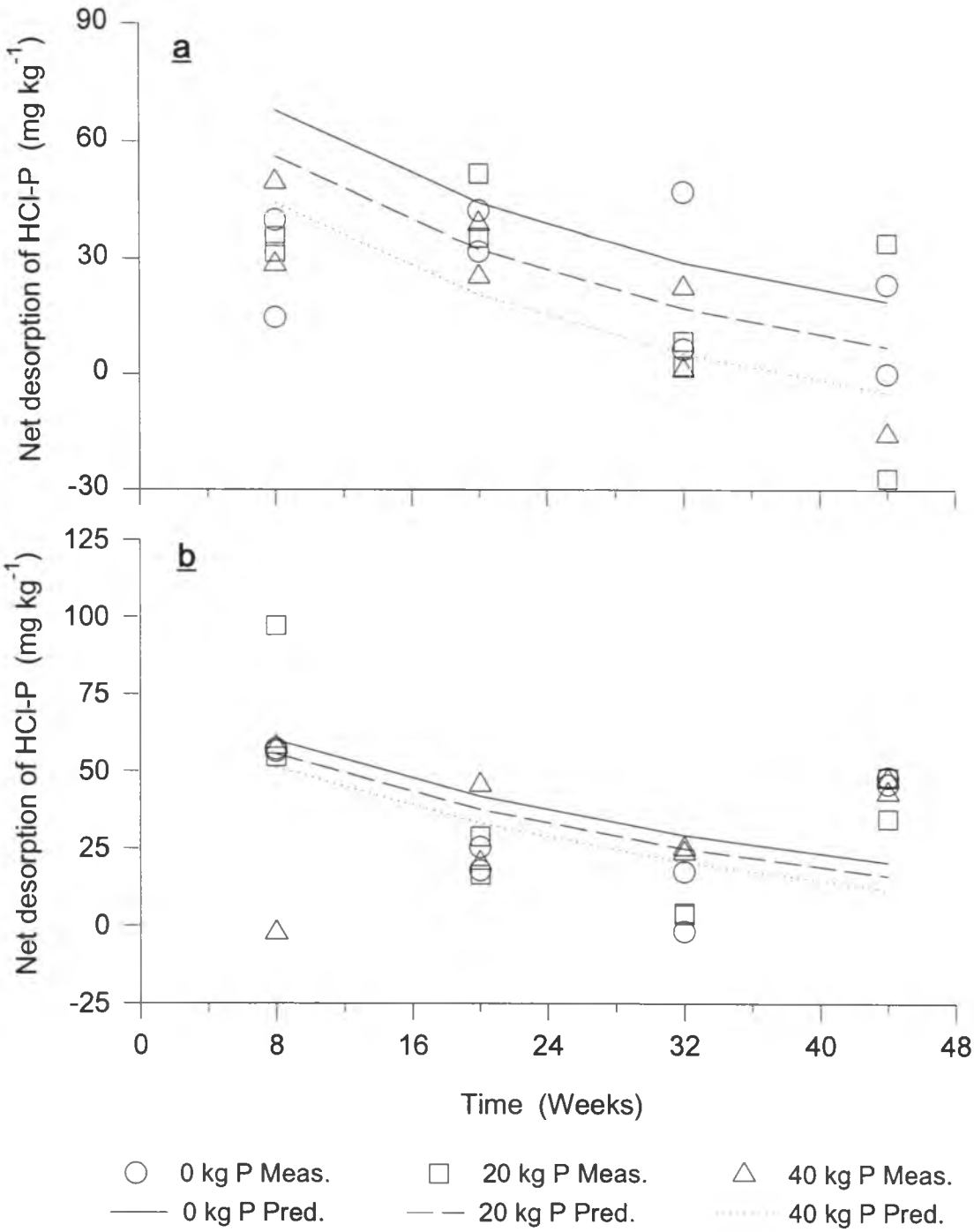


Figures 105a & b. Calculated and predicted net desorption of $NaHCO_3$-P of Purwodadi (a), and Madiun (b) soils.

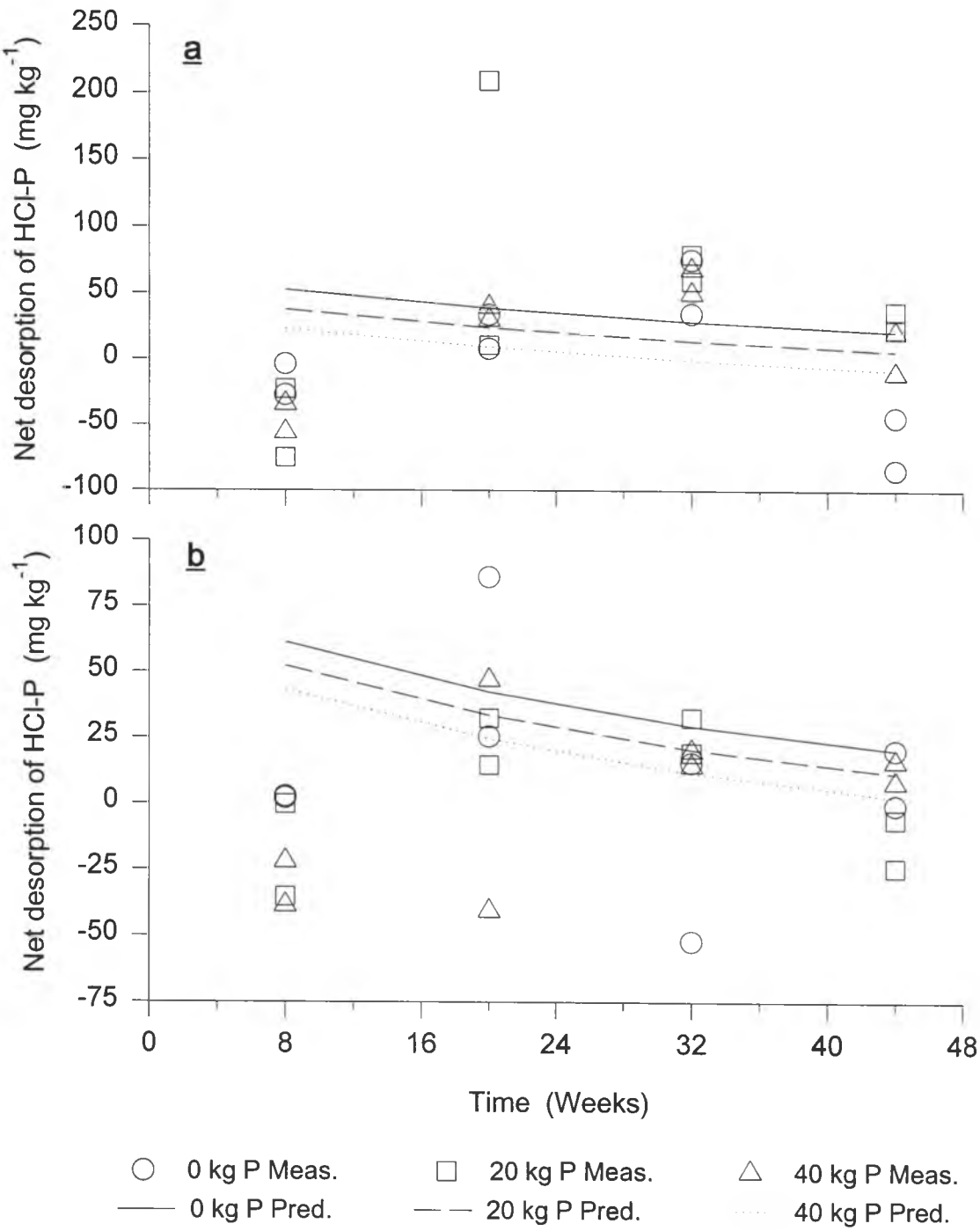


Figures 106a & b. Calculated and predicted net desorption of $NaHCO_3$-P of Mojokerto (a), and Jenggawah (b) soils.

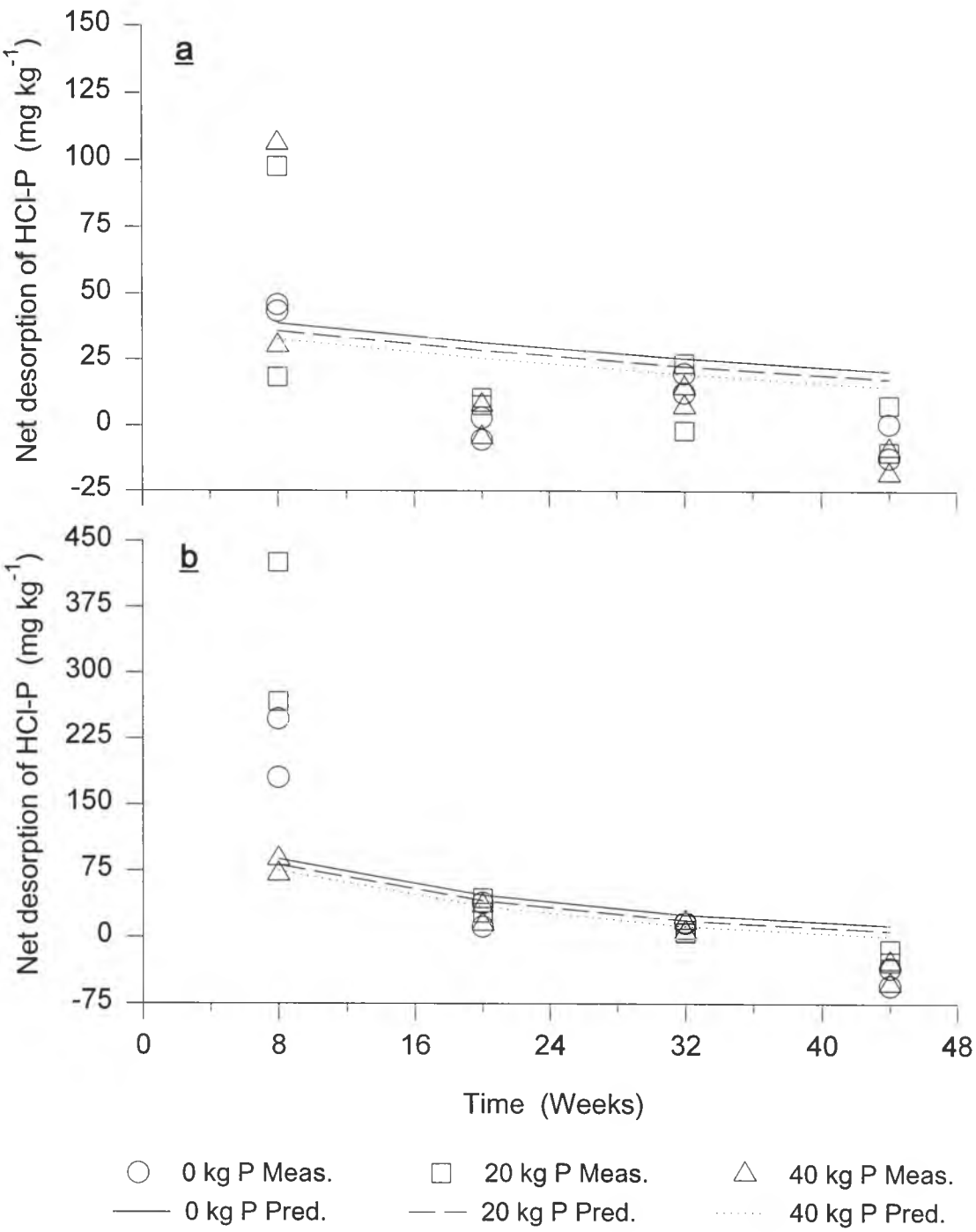
APPENDIX I. FIGURES 107a & b TO 109a & b. CALCULATED AND PREDICTED NET DESORPTION OF 25% HCl-RESIDUAL P



Figures 107a & b. Calculated and predicted net desorption of HCl-P of Cianjur (a), and Purbalingga (b) soils.



Figures 108a & b. Calculated and predicted net desorption of HCl-P of Purwodadi (a), and Madiun (b) soils.



Figures 109a & b. Calculated and predicted net desorption of HCl-P of Mojokerto (a), and Jenggawah (b) soils.

LITERATURE CITED

Adams, W.A., S.N. Gafoor, and M.I. Karim. 1987. Composition and properties of poorly ordered minerals in Welsh soils. II. Phosphate adsorption and reactivity towards NaF solution. Jour. Soil Sci. 38:95-103.

Afif, E., A. Matar and J. Torrent. 1993. Availability of phosphate applied to calcareous soils of West Asia and North Africa. Soil Sci. Soc. Amer. Jour. 57::756-760.

Appelt, H., N.T. Coleman, and P.F. Pratt. 1975. Interaction between organic compounds minerals, and ions in volcanic-ash-derived soils: II. Effects of organic compounds on the adsorption of phosphate. Soil Sci. Soc. Amer. Proc. 39:628-630.

Araki, S., H. Hirai, and K. Kyuma. 1986. Phosphate absorption of red and/or yellow colored soil materials in relation to the characteristics of free oxides. Soil Sci. Plant Nutr. 32:609-616.

Barrow, N.J. 1980. Evaluation and Utilization of Residual Phosphorus in soils. *In* Khasawneh, F.E., E.C. Sample, and E.J. Kamprath. 1980. The role of phosphorus in agriculture. American Society of Agronomy, Crop Science Society of America, Soil Science Society of America, Madison, Wisconsin. p 333-359.

Barrow, N.J. 1987. Reactions with variable-charge soils. Martinus Nijhoff Pub., Dordrecht.

Barrow, N.J. and E.D. Carter. 1978. A modified model for evaluating residual phosphate in soil. Austr. Jour. Agric. Res., 29:1011-1021.

Barrow, N.J., and T.C. Shaw. 1975. The slow reactions between soil and anions. 2. Effects of time and temperature on the decrease in phosphate concentration in the solution. Soil Sci., 119:167-177.

Barrow, N.J., and T.C. Shaw. 1979. Effects of ionic strength and nature of the cation on desorption of phosphate from soil. Jour. Soil Sci. 30:53-65.

Bennoah, E.O., and D.K. Acquaye. 1989. Phosphate sorption characteristics of selected major Ghanian soils. Soil Sci. 148:114-123.

Berkheiser, V.E., J.J. Street and T.L. Yuan. 1980. Partitioning of inorganic orthophosphate in soil-water systems. CRC Critical Review of Environmental Control. 10:179-224.

Birowo, A.T. 1975. Bimas: A Package Program for Intensification of Food Crop Production in Indonesia. SEADAG Papers on Problems of Development in Southeast Asia. The Asia Society-SEADAG. 23p.

Borggaard, O.K. 1983. The influence of iron oxides on phosphate adsorption by soil. Jour. Soil Sci. 34:333-341.

Borland International. 1994. QUATTROPRO® ver 5.0 for WINDOWS®

Bowden, J.W., S. Nagarajah, N.J. Barrow, A.M. Posner, and J.P. Quirk. 1980. Describing the adsorption of phosphate, citrate, and selenite on a variable-charge mineral surface. Austr. Jour. Soil Res. 18:49-60.

Buchter, B., B. Davidoff, M.C. Amacher, C. Hinz, I.K. Iskandar, and H.M. Selim. 1989. Correlation of Freundlich K_d and n retention parameters with soils and elements. Soil Sci. 148:370-379.

Cox, F.R, E.J. Kamprath, and R.E. McCollum. 1981. A descriptive model of soil test nutrient levels following fertilization. Soil Sci. Soc. Amer. Jour., 45:529-533.

Diamond, S. and E.B. Kinter. 1958. Surface areas of clay minerals as derived from measurements of glycerol retention. Clay and Clay Minerals, Nat. Acad. Sci. - Nat. Res. Council pub. 566, p:334-347.

Ditjen. Tanaman Pangan. 1994. Kebijaksanaan penggunaan pupuk pada tanaman pangan. Disajikan pada Training workshop penerapan uji tanah untuk meningkatkan hasil pertanian dan memelihara lingkungan. Pusat Penelitian Tanah dan Agroklimat-Bogor bekerjasama dengan Direktorat Usahatani dan Pengolahan Hasil Tanaman Pangan dan Hortikultura-Jakarta dan FADINAP-FAO, Bangkok. Technical Paper.

Environmental Systems Research Institute, Inc. (ESRI). 1992. ARC command reference. ESRI, Inc.

_____. 1992. ARCEDIT command reference. ESRI, Inc.

_____. 1992. ARCPLOT command reference. ESRI, Inc.

_____. 1993. ARC Macro Language. Developing ARC/INFO menus, and macros with AML. Revs 6 & 7 for workstation. ESRI, Inc.

Fakultas Pertanian - Institut Pertanian Bogor. 1992. Tahun 1963 Perguruan Tinggi Menjawab Tantangan Masalah Pangan. Insititut Pertanian Bogor.

Fixen, P.E. and A.E. Ludwick. 1982. Residual available phosphorus in near-neutral and alkaline soils: II. Persistence and quantitative estimation. Soil Sci. Soc. Amer. Jour., 46:335-338.

Fox, R.L. and P.G.E. Searle. 1978. Phosphate adsorption by soils of the tropics. *In* Diversity of soils of the tropics. ASA Special Publication No. 34. ASA, Madison, WI.

Gifford, R.M., J.D. Kalma, A.R. Aston, and R.J. Millington. 1975. Biophysical constraints in Australian food production. Implications for population policy. Search, 6:212-223.

Gomez, K.A. and A.A. Gomez. 1984. Statistical procedures for agricultural research. 2nd Edition. John Wiley & Sons Publication. 680p.

Griffin, R.A., and J.J. Jurinak. 1973. The interaction of phosphate with calcite. Soil Sci. Soc. Amer. Proc. 37:847-850.

Griffin, R.A., and J.J. Jurinak. 1974. Kinetics of the phosphate interaction with calcite. Soil Sci. Soc. Amer. Proc. 38:75-79.

Harter, R.D. 1969. Phosphorus adsorption sites in soils. Soil Sci. Soc. Amer. Proc. 33:630-632.

Hingston, F.J., R.J. Atkinson, A.M. Posner, and J.P. Quirk. 1968. Specific adsorption of anions on goethite. Trans. 95th Int. Cong. Soil Sci. 1:669-678.

Hingston, F.J., A.M. Posner, and J.P. Quirk. 1972. Anion adsorption by goethite and gibbsite. 1. The role of the proton in determining adsorption envelopes. Jour. Soil Sci. 23:177-192.

Hue, N.V. 1991. Effect of organic acids/anions on P sorption and phytoavailability in soil with different mineralogies. Soil Sci. 152(6):463-471.

Hulsebosch, T. 1995. Personal Communication.

Jackman, J.M. 1994. The phosphorus sorption potential of selected Hawai'ian soils in relation to their mineralogy and chemistry. MSc. Thesis. Univ. of Hawai'i at Manoa.

Jandel Scientific Software. 1994. SIGMA PLOT Scientific Graphic Software for WINDOWS®

Janssen, B.H., and J. Wolf. 1988. A simple equation for calculating the residual effect of phosphorus fertilizers. Fertilizer Research. 15:79-87.

Juo, A.S.R. 1981. Chemical characteristics. *In* D.J. Greenland (ed.) *Characterization of soils*. Clarendon Press, Oxford, pp. 55-79.

Kamprath, E.J. 1967. Residual effect of large applications of phosphorus on high phosphorus fixing soils. Agronomy Journal, 59:25-27.

Karama, S. A. 1993. Personal communication. Centre for Soil and Agroclimate Research, Bogor-Indonesia.

Kuo, S., and E.G. Lotse .1972. Kinetics of phosphate adsorption by calcium carbonate and Ca-kaolinite. Soil Sci. Soc. Amer. Proc. 36:725-729.

Larsen, S. 1967. Soil phosphorus. Adv. Agron., 19:151-210.

Larsen, S. 1974. Food. Netherland Jour. Agric. Sci., 22:270-274.

Leamer, R.W. 1963. Residual effects of phosphorus fertilizer in an irrigated rotation in the South West. Soil Sci. Soc. Amer. Proc. 27:65-68.

Li, Z.C., F.R. Cox, R.S. Yost, and G.M. Chen. 1995. Quantitative prediction of extractable P and the effect of crop uptake on extractable P. (in preparation).

Lins, I.D.G., F.R. Cox, and J.J. Nicholaides, III. 1985. Optimizing phosphorus fertilization rates for soybeans grown on Oxisols and associated Entisols. Soil Sci. Soc. Amer. Jour., 49:1457-1460.

Loganathan, P., N.O. Isirimah, and D.A. Nwachuku. 1987. Phosphorus sorption by Ultisols and Inceptisols of the Niger delta in southern Nigeria. Soil Sci. 144:330-338.

Matar, A. E. 1989. A descriptive model for prediction of residual P in soil after phosphate fertilization. International Center for Agricultural Research in Dry Areas (ICARDA), Syria. p:29-40.

Matar, A.E., E. Jabbour, and K. El Haji. 1988. Prediction of barley response to fertilizers by means of soil nitrogen and phosphorus tests. p. 12-23. *In* Matar et al. (editors), Proceeding of workshop on soil test calibration in West Asia and North Africa, Ankara, Turkey, 1-6 September 1987. ICARDA, Aleppo, Syria.

McNally, R. 1991. The Great Geographical Atlas. Rand Mc.Nally and Co. Publisher.

McLean, E.O. 1982. Soil pH and lime requirement. *In* Page, A.L., R.H. Miller, and D.R. Keeney. Methods of soil analysis. Part 2-Chemical and Microbiological Properties. Second Edition. ASA. SSSA. 199-224.

Moersidi, S., D. Santoso, M. Soepartini, M. Al-Jabri, J. Sri Adiningsih, and Sudjadi. 1989. Map of phosphorus requirements of lowland rice soils in Java and Madura. Pemberitaan Penelitian Tanah dan Pupuk, Pusat Penelitian Tanah Bogor, 8:13-25.

Moersidi, S., D. Santoso, M. Soepartini, M. Al-Jabri, J. Sri Adiningsih, and Sudjadi. 1993. Third edition of map of phosphorus requirements of lowland rice soils in Java and Madura. Pusat Penelitian Tanah Bogor.

Murphy, J. and J.P. Riley. 1962. A modified single solution method for the determination of phosphate in natural waters. Anal. Chem. Acta. 27:31-36.

Naidu, R., J.K. Syers, R.W. Tillman, and J.H. Kirkman. 1990. Effect of liming on phosphate sorption by acid soils. Jour. Soil Sci. 41:165-175.

Norrish, K. and H. Rosser. 1983. Mineral Phosphate, chapter 24. *In* Soils: An Australian Viewpoint. CSIRO.

Nursyamsi, D., D. Setyorini, and I.P.G. Widjaja-Adhi. 1993. Penentuan kelas hara P terekstrak beberapa pengekstrak dengan metode analisis keragaman yang dimodifikasi. Prosiding Pertemuan Teknis Penelitian Tanah dan Agroklimat Bidang Kesuburan dan Produktivitas Tanah. Bogor, 18-21 Februari 1993. Pusat Penelitian Tanah dan Agroklimat, p:217-235.

Nursyamsi, D., M. Soepartini, A.M. Damdam, Syarifuddin, and J. Sri Adiningsih. 1994. Pemilihan metode ekstraksi tanah sawah di Sulawesi Selatan. Risalah Seminar Hasil Penelitian Tanah dan Agroklimat th. 1994. Pusat Penelitian Tanah dan Agroklimat, p:1-12.

Olsen, S.R. and F.E. Khasawneh. 1980. Use and limitation of physical-chemical criteria for assessing the status of phosphorus in soils. *In* F.E. Khasawneh, E.C. Sample and E.J. Kamprath (eds). The Role of Phosphorus in Agriculture. ASA, CSSA, SSSA. Madison, Wisconsin.

Parfitt, R.L., R.J. Atkinson, and R.S.C. Smart. 1975. The mechanism of phosphate fixation by iron oxides. Soil Sci. Soc. Amer. Proc. 39:837-841.

Parfitt, R.L. 1978. Anion adsorption by soils and soil materials. Adv. Agronomy. 30:1-50.

Patrick, W.H., and I.C. Mahapatra. 1968. Transformation and availability to rice of nitrogen and phosphorus in waterlogged soils. Adv. Agron. 20:323-359.

Ponnamperuma, F.N. 1985. Chemical kinetics of wetlands rice soils relative to soil fertility. *In* Wetland Soils: Characterization, Classification, and Utilization. International Rice Research Institute, Los Banos, Laguna, Philippines, pp. 71-79.

Pusat Penelitian Tanah (CSAR). 1966. Peta tanah untuk Jawa Timur, Jawa Tengah, dan Jawa Barat skala 1:250 000. Pusat Penelitian Tanah Bogor.

Pusat Penelitian Tanah dan Agroklimat (CSAR). 1993. Peta keperluan fosfat tanah sawah. Propinsi Jawa Timur, Jawa Tengah, dan Jawa Barat. Edisi III.

Rajan, S.S.S. and R.L. Fox. 1975. Phosphate adsorption by soils. II. Reactions in tropical acid soils. Soil Sci. Soc. Amer. Proc. 39:846-851.

Richards, L.A. 1965. Physical condition of water in soil. *In* Black, C.A., D.D. Evans, J.L. White, L.E. Ensminger, and F.E. Clark. 1965. Methods of soil analysis. Part 1. Physical and mineralogical properties, including statistics of measurement and sampling. Agronomy No. 9. American Society of Agronomy, Inc. p:128-152.

Ru-kun, L., J. Bai-fan, and L. Ching-kwei. 1982. Phosphorus management for submerged soil. Proc. 12th Int. Cong. Soil Sci., Symposia Paper II. Indian Soc. Soil Sci., New Delhi, p:182-191.

Russell, J.S. 1977. Evaluation of residual nutrients in soils. Austr. Jour. Agric. Res., 28:461-475.

Ryden, J.C., and P.F. Pratt. 1980. Phosphorus removal from wastewater applied to land. Hilgardia 48:1-36.

Sadler, J.M., and J.W.B. Stewart. 1974. Residual fertilizer phosphorus in western Canadian oils: a review. Saskatchewan Inst. of Pedology no. R136.

Sah, R.N., and D.S. Mikkelsen. 1986a. Transformations of inorganic phosphorus during the flooding and draining cycles of soil. Soil Sci. Soc. Amer. Jour. 50:62-67.

Sah, R.N., and D.S. Mikkelsen. 1986b. Effects of anaerobic decomposition of organic matter on sorption and transformations of phosphate in drained soils: 2. Effects on amorphous iron content and phosphate transformation. Soil Sci. 142:346-351.

Sah, R.N., and D.S. Mikkelsen. 1989. Phosphorus behavior in flooded-drained soils. I. Effects on phosphorus sorption. Soil Sci. Soc. Amer. Jour. 53:1718-1722.

Sah, R.N., D.S. Mikkelsen, and A.A. Hafez. 1989. Phosphorus behavior in flooded-drained soils. III. Phosphorus desorption and availability. Soil Sci. Soc. Amer. Jour. 53:1729-1732.

Sample, E.C., R.J. Soper, and G.J. Racz. 1980. Reactions of phosphate fertilizer in soils. *In* Khasawneh, F.E., E.C. Sample, and E.J Kamprath. 1980. The role of phosphorus in agriculture. American Society of Agronomy, Crop Science Society of America, Soil Science Society of America, Madison, Wisconsin. p263-310.

Sanchez, P.A. and G. Uehara. 1980. Management considerations of four acid soils with high phosphorus fixation capacity. *In* F.E. Khasawneh, E.C. Sample, and E.J. Kamprath (eds). The role of phosphorus in agriculture. ASA, Madison, WI.

Santoso, D. and Sudjadi. 1974. Tanah sawah memerlukan fosfat di Jawa dan Madura. Laporan bagian kesuburan tanah. No. 36A. Puslit Tanah, Bogor. 25p.

Sanyal, S.K., and S.K. De Datta. 1991. Chemistry of phosphorus transformations in soil. *In* Stewart, B.A. 1991. Advances in Soil Science. Vol. 16:1-120.

SAS Institute Inc. 1993. SAS® for UNIX® User's Guide: Statistics,. Version 6.09 Edition. Cary, North Carolina.

Skempton, A.W. 1953. The colloidal "activity" of clays. Proc. 3rd Int Conf. Soil Mech. and Found. Eng. 1:57-61.

Smillie, G.W., D. Curtin, and J.K. Syers. 1987. Influence of exchangeable calcium on phosphate retention by weakly acid soils. Soil Sci. Amer. Jour. 51:1169-1172.

Soil Science Society of China. 1983. Methods of soil, plant, and fertilizer analyses. Science Press. Beijing. PRC. p:95-97.

Sowers, G.F. 1965. Consistency. *In* Black, C.A., D.D. Evans, J.L. White, L.E. Ensminger, and F.E. Clark. 1965. Methods of soil analysis. Part 1. Physical and mineralogical properties, including statistics of measurement and sampling. Agronomy No. 9. American Society of Agronomy, Inc. Academic Press, New York. p. 391-399.

Sri Adiningsih, J., Sri Rochayati, Diah Setyorini, and M. Sudjadi. 1988. Efisiensi penggunaan pupuk pada lahan sawah. Makalah disajikan dalam Simposium Penelitian Tanaman Pangan II, Puncak (Bogor), 21-23 Maret 1988. (Mimeograph).

Sri Adiningsih, J., and IPG Widjaja-Adhi. 1994. Personal Communication.

Sri Adiningsih, J. 1994. Pengelolaan pupuk pada sistem usaha tani lahan sawah. Technical Paper presented at Training Workshop Penerapan Uji Tanah untuk Meningkatkan Hasil Pertanian dan memelihara Lingkungan. Kerjasama Pusat Penelitian Tanah dan Agroklimat-Bogor - Direktorat Bina Usahatani dan Pengolahan Hasil Tanaman Pangan dan Hortikultura-Jakarta - FADINAP-FAO, Bangkok. Technical Paper.

Sri Rochayati, Mulyadi, and J.S. Adiningsih. 1990. Penelitian efisiensi penggunaan pupuk di lahan sawah. (An evaluation on the efficiency of fertilizers application In paddy soils). Prosiding Lokakarya Nasional Efisiensi Penggunaan Pupuk V, Cisarua, Bogor 12-13 Nopember 1990. Pusat Penelitian Tanah dan Agroklimat. Bogor-Indonesia. 107-143.

Sudjadi, M. and I.M.W. Suranta. 1983. Penuntun analisa tanaman. Buletin Tehnik Penelitian Tanah No. 1. Pusat Penelitian Tanah Bogor.

Supriyo, H., N. Matsue, and N. Yoshinaga. 1992. Chemistry and Mineralogy of some soils from Indonesia. Soil Sci. Plant Nutr., 38(2):217-225.

Suranta, I.W., M. Sudjadi, and N.S. Mulyani. 1989.. Penuntun analisa tanah dan air untuk klasifikasi tanah dan evaluasi lahan. Pusat Penelitian Tanah dan Agroklimat Bogor (CSAR).

Uehara, G. and G. Gillman. 1981. The mineralogy, Chemistry, and Physics of Tropical soils with variable charge clays. Westview Press. Colorado. 170p.

U.S. Department of the Army. 1994. Indonesia - Country Study. Accessed through World Wide Web, URL at http: //umslvma.umsl.edu/11/LYBRARY/ GOVDOCS/ARMYAYHBS/AAHB8.

Venables, W.N. and B.D. Ripley. 1994. Modern Applied Statistics with S-Plus. Springer-Verlag. 462p.

Wada, K., L. Xue-yuan, and P.W. Moody. 1989. Chemistry of adverse upland soils. Paper presented at the Symposium on Phosphorus Requirements for Sustainable Agriculture in Asia and Oceania, 6-10 March 1989, International Rice Research Institute, los Banos, Laguna, Philippines.

Wade, M.K. and I.P.G. Widjaja-adhi. 1988. Phosphorus fertilizer management and P availability on a high sorption tropical soil. Pemb. Penel. Tanah dan Pupuk 6:32-39.

Watanabe, F.S., and S.R. Olsen. 1965. Test of an ascorbic acid method for determining phosphorus in water and $NaHCO_3$ extracts from soil. Soil Sci. Soc. Amer. Proc. 29:677-678.

Way, J.T. 1850. On the power of soils to absorb manure. Jour. Royal Agric. Soc. Engl. 11:313-379.

Wibowo, R. 1993. Pertimbangan sosial ekonomi kegiatan sektor pertanian berkaitan dengan penghapusan subsidi pupuk. Forum Eksplikasi sains Sosek Pertanian. Jurusan Sosial ekonomi Pertanian. Fakultas Pertanian Universitas Jember. Vol. 1 no. 2:p116-125.

Widjaja-Adhi, I.P.G. 1986. Penentuan kelas ketersediaan hara dengan metoda analisa keragaman yang dimodifikasi. Pemberitaan Penelitian tanah & Pupuk. No. 5:23-28.

Wiklander, L. 1950. Kinetics of phosphate exchange in soils. Ann. Res. Agric. Coll. (Sweden), 17:407-423.

Wild, A. 1950. The retention of phosphate by soil. A review. Jour. Soil Sci. 1:221-238.

Willet, I.R., and M.L. Higgins. 1978 Phosphate sorption by reduced and reoxidized rice soils. Australian Jour. Soil Res. 16:319-326.

Willett, I.R. 1982. Phosphorus availability in soils subjected to short periods of flooding and drying. Aust. J. Soil Res. 20:131-138.

Williams, E.G. 1952. Evaluating the phosphorus status of soils. Int. Soc. Soil Sci., Trans. Comm. II & IV (Dublin, Ireland, 21-31 July 1952), 1:31-47.

Wolf, J., C.T. de Wit, B.H. Janssen, and D.J. Lathwell. 1987. Modeling long-term crop response to fertilizer phosphorus. 1. The Model. Agronomy Journal. 79:445-451.

Yost, R.S., A.B. Onken, F. Cox, and S. Reid. 1992. The diagnosis of phosphorus deficiency and predicting phosphorus requirement. *In* Proceeding of the TropSoils, Phosphorus decision support system workshop. TropSoils Bulletin No. 92-02.